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Light Water Reactor Sustainability Research and Development Program Plan

Fiscal Year 2009–2013

December 2009

DOE Office of Nuclear Energy

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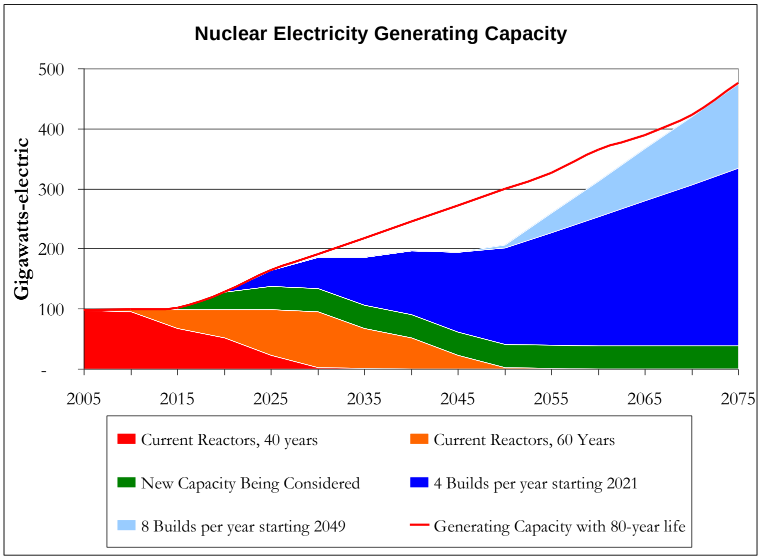
EXECUTIVE SUMMARY

Nuclear power has reliably and economically contributed almost 20% of electrical generation in the United States over the past two decades. It remains the single largest contributor (more than 70%) of non-greenhouse-gas-emitting electric power generation in the United States.

By the year 2030, domestic demand for electrical energy is expected to grow to levels of 16 to 36% higher than 2007 levels. At the same time, most currently operating nuclear power plants will begin reaching the end of their 60-year operating licenses. Figure E-1 shows projected nuclear energy contribution to the domestic generating capacity. If current operating nuclear power plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline—even with the expected addition of new nuclear generating capacity.



The red line represents the total generating capacity of current and planned nuclear power plants, assuming extended operation to 80 years. The unshaded area below the line represents lost capacity if the current nuclear power plant fleet is decommissioned after 60 years.

Figure E-1. Projected nuclear power generation.

The oldest commercial plants in the United States reached their 40th anniversary this year. U.S. regulators have begun considering extended operations of nuclear power plants and the research needed to support long-term operations. The Light Water Reactor Sustainability (LWRS) Research and Development (R&D) Program, developed and sponsored by the Department of Energy, is performed in close collaboration with industry R&D programs. The purpose of the LWRS R&D Program is to provide technical foundations for licensing and managing long-term, safe and economical operation of the current operating nuclear power plants.

The LWRS R&D Program vision is captured in the following statements:

Existing operating nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license-extension period, significantly contributing to reduction of United States and global carbon emissions, enhancement of national energy security, and protection of the environment.

There is a comprehensive technical basis for licensing and managing the long-term, safe, economical operation of nuclear power plants. Sustaining the existing operating U.S. fleet also will improve its international engagement and leadership on nuclear safety and security issues.

The following five R&D pathways have been identified to achieve the program vision:

Nuclear Materials Aging and Degradation. Research to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. Provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operation.

Advanced LWR Nuclear Fuel Development**.** Improve scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics.

Advanced Instrumentation, Information, and Control Systems Technologies**.** Address long-term aging and obsolescence of instrumentation and control technologies and develop and test new information and control technologies. Develop advanced condition monitoring technologies for more automated and reliable plant operation

Risk-Informed Safety Margin Characterization**.** Bring together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management.

Economics and Efficiency Improvement. Improve economics and efficiency of the current fleet of reactors while maintaining excellent safety performance. Develop methodologies and scientific basis to enable more extended power uprates or ultra high power uprates. Improve thermal efficiency by developing advanced cooling technologies to minimize water usage. Study the feasibility of expanding the current fleet into nonelectric applications.

With the 60-year licenses beginning to expire between the years 2029 and 2039, utilities are likely to initiate planning baseload replacement power by 2014 or earlier. Research for addressing nuclear power plant aging questions must start now and is likely to extend through 2029. The LWRS R&D Program represents the timely collaborative research needed to retain the existing nuclear power plant infrastructure in the United States.

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ACRONYMS

CO_2	carbon dioxide
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy-Idaho Office
DSA	deterministic safety analysis
EPRI	Electric Power Research Institute
FY	fiscal year
II&C	instrumentation, information, and control
INL	Idaho National Laboratory
LWR	light water reactor
LWRS	light water reactor sustainability
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk analysis
R&D	research and development
RISMC	risk-informed safety margin characterization
SiC	silicon carbide
SiC/SiC_f	silicon carbide/silicon carbide fiber (reinforced)
SSC	systems, structures, and components
TIO	Technical Integration Office

Light Water Reactor Sustainability Research and Development Program Plan

1. PURPOSE OF THE PROGRAM

1.1 Introduction

The electric energy sector is entering a time of serious challenge and tremendous opportunity. Expanding energy demand and a growing awareness of the environmental impact caused by various forms of electricity generation have prompted debate on how best to achieve a sustainable, affordable, and environmentally sensitive energy solution. Nuclear power is integral to meeting that objective.

The Light Water Reactor Sustainability (LWRS) Program is a research and development (R&D) program sponsored by the U. S. Department of Energy (DOE), performed in close collaboration with industry R&D programs, with the aim to provide technical foundations for licensing and managing the long-term safe and economical operation of current nuclear power plants. DOE's program focus is on the longer term and higher risk/reward research that contributes to the national policy objectives of energy security and reduction of carbon dioxide (CO_2) emissions.

Electric power is a vital component of the nation's economy and way of life. As the energy needs of the United States grow over the coming decades, the national energy supply faces growing pressures on global and domestic scales. In 2006, 70% of domestic electricity generation relied on fossil fuels. Greenhouse gas emissions from these fossil fuels are a mounting problem that threatens the future production of electricity from coal and natural gas. President Obama has called for a reduction of CO_2 emissions to the 1990 levels by the year 2020, with a further 80% reduction by the year 2050. Meeting these aggressive goals while gradually increasing the overall energy supply requires that all nonemitting technologies must be advanced.

Nuclear power is the largest contributor of non-greenhouse-gas-emitting electric power generation, comprising nearly three-quarters of the nonemitting sources as shown in Figure 1-1. Energy efficiency and carbon storage are expected to play increasing roles in providing clean, reliable energy; however, nuclear power will be depended on well into the 21st century for a large-scale supply of dependable clean electricity.

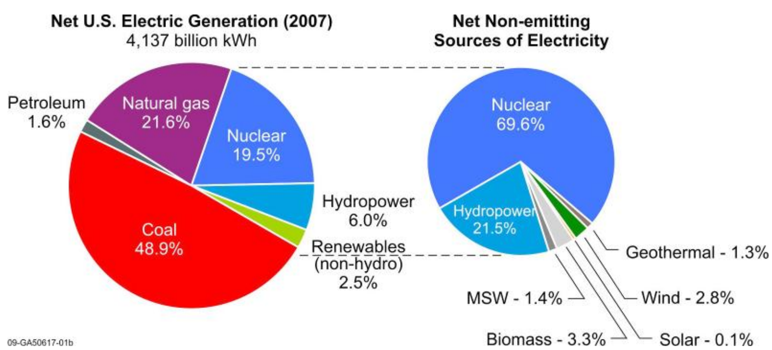

Figure 1-1. Current electric generating portfolio showing dominance of nuclear as low carbon emission power source.

Other forms of low CO_2-emitting and renewable energy production also have the potential to produce environmentally friendly energy. Among the most promising forms of energy production are hydroelectric, wind, geothermal, and solar power. Hydroelectric power is the most widely used renewable energy in the United States; however, there is limited opportunity for expansion. Wind, geothermal, and solar power have demonstrated promise in producing environmentally friendly energy to meet the nation's growing demand. These sources of power have been deployed only recently and they currently contribute only a small fraction of the nation's rapidly growing energy demands. In addition, wind and solar power, by nature, are dilute with low power density and a low capacity factor. Figure 1-2 provides a graph of current capacity factors by energy source. The very high capacity factor for nuclear power makes it the only reliable and nearly non-CO_2-emitting source of baseload power available.

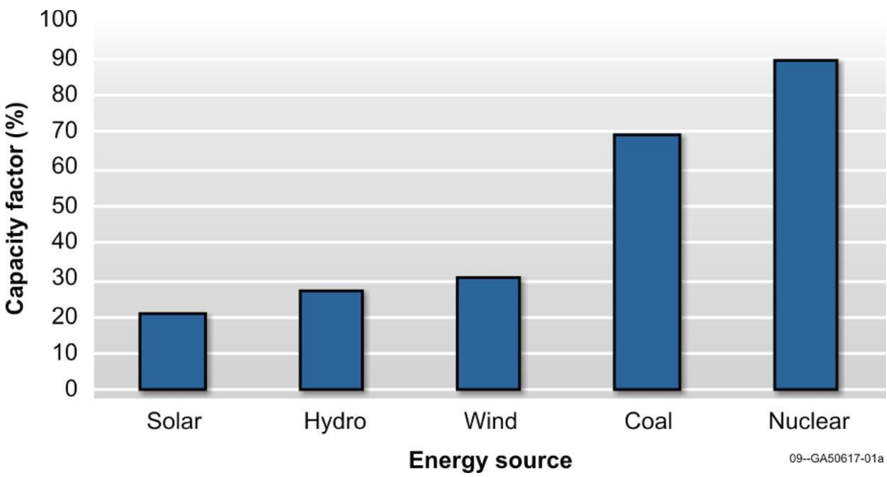

Figure 1-2. United States electrical generation capacity factors by energy source showing high operating performance.

The National Energy Policy Act of 2005 established and authorized the DOE's Nuclear Power 2010 Program to stimulate construction of new nuclear power plants with demonstration of streamlined but unproven licensing processes and facilitating "first mover" new nuclear power plants. Construction of new nuclear power plants is a clear option for new, emission-free, electrical generating capacity.

As of July 2009, 18 combined operating license applications have been submitted to construct 28 new nuclear power plants.[a] Over 30 proposed nuclear power plants currently are in the planning or licensing stage, making it clear that new plant construction is an option that is being pursued seriously. However, bringing new nuclear power plants online is facing substantial challenges and uncertainties, including formidable high capital cost, high financing cost, long construction time, limitations in domestic fabrication capacity, and small market values. It is anticipated that there will be a modest pace of construction of new nuclear power plants. Only a fraction of the planned new nuclear power plants might be built, as evidenced by the fact that, as of today, no utility has committed to constructing a new advanced reactor. Each nuclear power plant currently under consideration is expected to be capable of producing between 1.1 and 1.7 GWe, depending on design.

On the other hand, 104 nuclear power plants currently operate in 31 states (Figure 1-3). The existing, operating fleet of U.S. nuclear power plants has consistently maintained outstanding levels of nuclear safety, reliability, and operational performance over the last two decades and operates with an average capacity factor above 90%, far superior to the 70% capacity factor a decade ago.[b] This significant improvement in performance has made nuclear power plants considerably more economical to operate. Major improvements were made in all areas of plant operation, including operations, training, equipment maintenance and reliability, technological improvements, and improved understanding of component degradation. More broadly, these improvements reflect effective management practices, advances in technology, and the sharing of safety and operational experience. Today, nuclear production costs are the lowest among major U.S. power-generating options.

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[a] U.S. Department of Energy Nuclear Power 2010, *Nuclear Power Deployment Scorecard*, http://nuclear.energy.gov/np2010/neScorecard/neScorecard.html, web page updated July 14, 2009, web page visited July 28, 2009.

[b] Blake, Michael E., "U.S. capacity factors: Another small gain, another new peak," *Nuclear News*, May 2008, pp. 28-34.

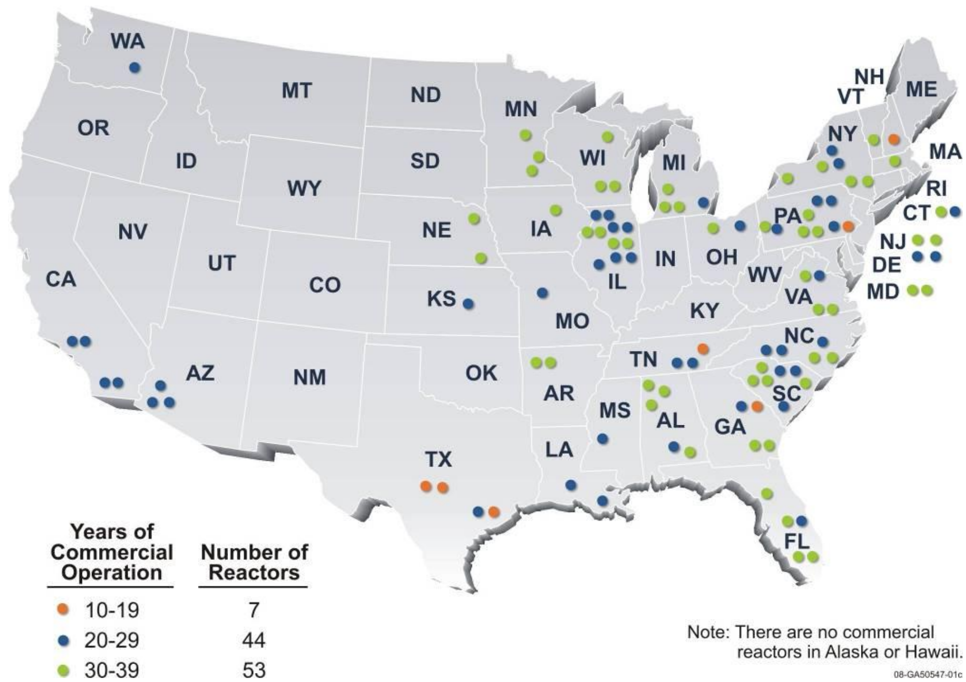

Figure 1-3. National distribution of operating nuclear power plants.

Most operating nuclear power plants have obtained, are applying, or intend to apply for license extension. Figure 1-4 shows the following: (1) the oldest nuclear power plant started operation in 1969 and the newest plant started operation in 1996, (2) the first group of nuclear power plants were brought online between 1969 and 1979 and the second group between 1980 and 1996, and (3) all most all operating nuclear power plants have been issued, are applying for, or plan to apply for a 20-year license extension. This license extension will result in a licensed operating life of 60 years.

In about the year 2030, unless further licensing renewal occurs the current fleet of nuclear power plants will start decommissioning. Absent additional research to address critical plant-aging issues, these valuable generating stations may be retired after reaching 60 years of operation. Furthermore, with the state of present research, degradation and obsolescence threaten to decrease power production from these nuclear power plants even before their scheduled end of licensed lifetimes. Over the next three decades, this would result in a loss of 100-GWe, emission-free generating capacity and is comparable to electrical generation of new nuclear power plants built over the same time period, leaving a gap in projections of required emission-free generating capacity. This gap might be filled with higher construction rates of new nuclear power plants or with other technologies. However, continued safe and economical operation of current reactors for an even longer period of commercial operation, beyond the current license renewal lifetime of 60 years, is a low-risk option to fill the gap and to add new power generation at a fraction of the cost of building new plants.

In order to receive a 20-year license extension, a nuclear power plant operator must ensure that the plant will operate safely for the duration of the license extension. The 40-year operating license period established in the Atomic Energy Act was based on antitrust considerations, not technical limitations. The 20-year license extension periods are presently authorized under the governing regulation of 10 CFR Part 54, “Requirements for Renewal of Operating Licenses for Nuclear Power Plants.” This rule places no limit on the number of times a plant can be granted a 20-year license renewal as long as the licensing basis is maintained during the renewal term in the same manner and to the same extent as during the original licensing term.

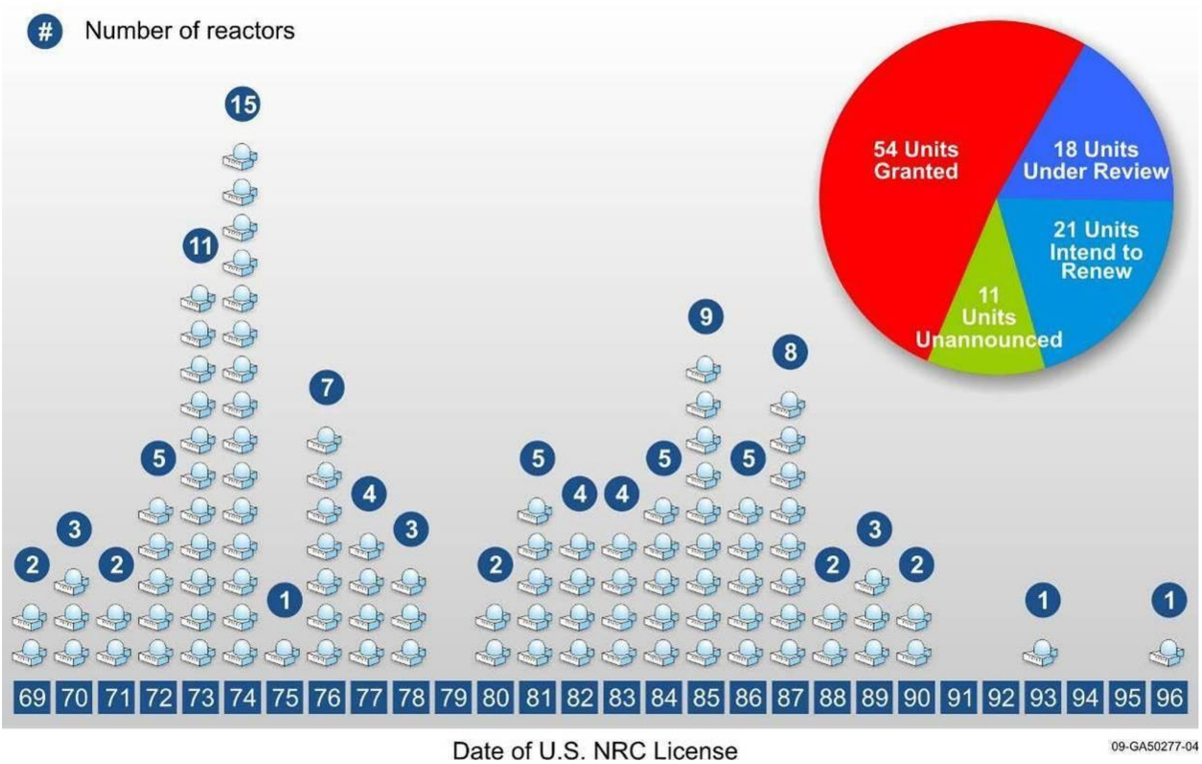

Figure 1-4. Nuclear power plant initial license date and license extension plans.

This regulatory process ensures continued safety of all currently operating nuclear power plants during future renewal periods. The license extension process requires a safety review and an environmental review, with multiple opportunities for public involvement. The applicant must demonstrate safety issues through technical documentation and analysis, which the U.S. Nuclear Regulatory Commission (NRC) confirms before granting a license extension. A solid technical understanding of how systems, structures, and components (SSCs) age is necessary for nuclear power plants to demonstrate continued safety. A well-established knowledge base for the current period of licensed operation exists; however, additional research will be needed to obtain the same robust technical basis required for continued operational evaluations beyond 60 years.

In early 2007, DOE, with the Idaho National Laboratory (INL) engaging the Electric Power Research Institute (EPRI) and other industry stakeholders, initiated planning that lead to the LWRS R&D Program. The aim was to develop an R&D strategy that addresses nuclear energy issues within the framework of the National Energy Policy and the Policy Act of 2005. Based on considerable analysis and information gathering, the "*Strategic Plan for Light Water Reactor Research and Development*," was developed and reviewed by an independent committee of experts. The plan, which recommended ten top priority areas for a government-industry, cost-shared R&D program, was issued in November 2007.[c]

Building on the strategic plan and collaborative relationships that were developed while preparing it, DOE and INL immediately started developing the LWRS R&D Program. In February 2008, DOE and NRC sponsored a workshop, which identified necessary R&D for long-term operation and licensing of

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[c] NL/EXT-07-13543, *Strategic Plan for Light Water Reactor Research and Development*, Idaho National Laboratory, November 2007.

nuclear power plants.[d] Input from a large set of stakeholders provided important definition of needs and focused program objectives on long-term operation of existing nuclear power plants.

In developing the strategic plan and more specific program plans, it has become apparent that a government/industry cost sharing arrangement for R&D is desirable for addressing the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry. The LWRS R&D Program requires the long-term vision and support of national laboratories to address strategic reliability and safety requirements of existing nuclear power plants that could not be addressed by more inherently tactical organizations. The long-term, higher-risk research required to construct a scientific basis to understand the complex effects of plant aging is not likely to be carried out by industry alone.

While industry is likely to invest in applied research programs that are directed toward enhancing operations or in developing incremental improvements, industry is unlikely to invest significantly in research programs that focus on longer-term or higher-risk gains. Additionally, because research necessary for nuclear power plant life extension is of a broad nature that provides benefits to the entire industry, it is unlikely that a single company will make the necessary investment on its own. Government cost sharing and involvement will be required to promote the necessary programs that are of crucial long-term importance. The LWRS R&D Program, by incorporating long-term collaborative industry stakeholder inputs and shared costs, will support the strategic national interest of maintaining nuclear power as an available resource.

Over the past several decades, academia and national laboratories have made enormous advances in the area of general materials science and modeling of fundamental structures. Applications of these sciences, although not specifically nuclear in nature, have the potential to bring tremendous advances over the narrowly focused, step-wise improvements the nuclear industry has realized thus far. Additionally, because of their unique resources (such as experimental irradiation and post-irradiation examination facilities), the national laboratory infrastructure is positioned to bridge the nuclear industry, R&D, and demonstration infrastructures. The LWRS R&D Program serves to facilitate use of this knowledge with further R&D that is specific to the current fleet of nuclear power plants in understanding ongoing and complex challenges to long-term operations.

In summary, the electrical energy sector is challenged to supply increasing amounts of electricity in a dependable and economical manner and with reduced CO_2 emissions. Consistent with the National Energy Policy, nuclear power is an important part of answering the challenge through long-term safe and economical operation of current nuclear power plants and with building new nuclear power plants. The LWRS R&D Program is designed to provide, in collaboration with industry programs, the sound technical basis for licensing and managing the long-term safe operation of existing operating nuclear power plants.

1.2 Sustainability

Sustainability in the context of LWRs is defined as the ability to maintain safe and economic operation of the existing operating fleet of nuclear power plants for a longer than licensed lifetime. It has two facets with respect to long-term operations: (1) manage the aging of hardware so the nuclear power plant lifetime can be extended and the plant can continue to operate safely, efficiently and economically;

[d] "Life Beyond 60 Workshop Summary Report, NRC/DOE Workshop U.S. Nuclear Power Plant Life Extension Research and Development," U.S. Nuclear Regulatory Commission and U.S. Department of Energy, Prepared by Energetics Inc., Feb. 19-21, 2008.

and (2) provide science-based solutions to the industry to implement technology to exceed the performance of the current labor-intensive business model.

Programmatically, LWRS is dependent on a sequence of four successful phases: (1) utility's decision to invest in extending the nuclear power plant life beyond 60 years; (2) licensing and public confidence in the nuclear power plant life extension; (3) implementation of nuclear power plant refurbishment and upgrade to meet the licensing and enhanced performance requirements; and (4) safe and economic nuclear power plant operation for the intended period of the nuclear power plant life extension. While tightly coupled, each of the four sequential phases is critical to nuclear power generation on its own with a specific set of challenges. The four phases span over several decades, a feature important for planning and implementation of the supporting R&D program.

The industry must also have the confidence that these sustainability critical technologies and processes will be acceptable with the regulators. On the technical side, the key is to establish the availability of an adequate body of knowledge (e.g., data and methods) to assess characterizing nuclear power plant SSC, their aging behavior, and plant safety margins. On the regulatory side, it is important to account for evolution of the regulatory paradigm. Because of the long-term character of investing in LWRS, it is in the best interest of the industry that a predictable, science-based regulatory framework be established. Application of the new predictable science-based licensing concepts will provide additional confidence for the public and industry.

Through technological innovation, existing operating nuclear power plants have established a remarkable performance track record. However, as a plant ages, performance normally drops. The May 2009 issue of *Nuclear News* provides evidence that reactors in their fourth decade have not achieved results quite as impressive as those of newer reactors.[e] Without innovation, performance most likely will deteriorate even more when the older nuclear power plants enter their fifth and sixth decades. Therefore, new innovations and business models are needed in order to significantly enhance performance from today's high standard.

The new business model can be achieved through enabling transforming technology advancements and by leveraging the resources of the entire industry through seamless integration of plant owner/operator, suppliers, service providers and regulators. Nuclear power plant data and analysis tool interfaces would be standardized across the industry.

1.3 Critical Path for Nuclear Power Plants

Ultimately, extending the life of an existing asset is an individual utility business and risk decision. A utility anticipates that, in most situations, extending the life of an existing nuclear power plant is likely to cost less than building a new plant; however, operating costs must remain competitive. Individual owner-operators are likely to seriously consider extending the life of their existing nuclear power plants well in advance of committing to new construction, assuming existing assets can economically meet anticipated demand growth and assuming that the option to do so is still available. It is also likely that decisions of extending nuclear power plant lifetimes will be accompanied by facility upgrading and uprate assessments, thus helping to manage the operational risks of aging and taking advantage of technical enhancement opportunities. These capital-spending decisions will require a thorough business case and a technical understanding and predictability of aging and degradation risks.

Decisions to develop, construct, and license baseload generation must be made far in advance of power demands outgrowing supply capacities. Actions for retaining existing nuclear power infrastructure

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[e] "U.S. Capacity Factors: Can Older Reactors Keep Up the Pace?," *Nuclear News*, May 2009.

in the United States must begin in a timely manner. Given the risk-adverse influences of financial markets, state public utility/service commissions, and NRC, power-generating utilities must use all available information in carrying out these decisions. With extended operational lifetimes, aging-related technical or operational questions that did not exist previously have now become important decision factors.

Extending nuclear power plant life beyond 60 years is expected to remain a technically viable option for filling the power-generation gap between license expiration of older nuclear power plants and having newer nuclear power plants come online. In addition to the environmental benefits, extending the life of highly efficient existing nuclear power plants defers the up-front costs of building new nuclear power plants.

With the present 60-year licenses beginning to expire between the years of 2029 and 2039 for the first group of nuclear power plants that came online between 1969 and 1979 (as shown in Figure 1-4) utilities are likely to initiate planning of baseload replacement power by 2014 or earlier. If the option to extend current plant lifetimes is not available, strategic planning and investment required to maintain the current LWR fleet may not happen in a sustainable manner. The research window for supporting the utility's decisions to invest in lifetime extension and to support NRC decisions to extend the license must start now and is likely to extend through the following 20-year period (i.e., 2010 to 2029), with higher intensity for the first 10 years. The LWRS R&D Program represents the beginning of timely collaborative research needed to retain the existing nuclear power infrastructure of the United States.

2. DESCRIPTION

2.1 Vision

Today's commercial nuclear power plant fleet has reliably produced environmentally friendly power in the United States for decades. As these nuclear power plants reach the end of their original 40-year operating license and enter their first 20-year extended license, sound engineering principles used in designing and building them are being applied to demonstrate their continued safety for a possible second license extension. In order to preserve the option of continued safe and economical operation of these nuclear power plants, a technical basis is required for the utility to evaluate investments in life-extending improvements and for the regulator to accept license extension applications. This program plan identifies R&D activities for enhancing scientific understanding of aging mechanisms important to the SSCs in nuclear power plants and to develop methods and technologies for managing plant aging and evaluating safety of nuclear power plants for long-term operation.

The LWRS R&D Program vision is captured in the following statements:

Existing operating nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license-extension period, significantly contributing to reduction of United States and global carbon emissions, enhancement of national energy security, and protection of the environment.

There is a comprehensive technical basis for licensing and managing the long-term, safe, economical operation of nuclear power plants. Sustaining the existing operating U.S. fleet also will improve its international engagement and leadership on nuclear safety and security issues.

Extending the life of nuclear power plants is a vital step in meeting the electrical needs of the United States today and in decades to come. By keeping these plants safely in service, the nation will retain valuable infrastructure and allow additional time to construct new sources of clean, reliable, and secure energy. Until other reliable sources of power are built and placed on the electrical grid, the existing fleet of nuclear power plants is a vital component of the economy.

2.2 Program Goals

The LWRS R&D Program is designed to help achieve its vision by addressing long-term operational challenges that face nuclear utilities in the United States. Program goals are to develop scientific understanding, tools, processes, and technical and operational improvements to do the following:

1. Support long-term licensing and operation of the existing operating nuclear power plants to successfully achieve planned lifetime extension up to 60 years and lifetime extension beyond 60 years

2. Support maintenance and enhancement of performance of the existing operating fleet of LWRs to ensure superior safety, high reliability, and economic performance throughout their full lifetime.

2.2.1 Scientific Basis

Ensuring public safety and environmental protection is a prerequisite to all nuclear power plant operating decisions. For extended operating periods, it must be shown that adequate aging management programs are present or planned and that appropriate safety margins exist throughout the subsequent license renewal periods. Through research, this program will seek to contribute to the technical foundation on which licensees can base their analyses to determine if these adequate safety margins and superior economic performance can be maintained or even enhanced. In order to make the technically justified case when deciding to apply for a subsequent license extension, the nuclear industry will require definitive knowledge into the effects of aging. The scientific means (such as sound fundamental understanding) and transformative technologies (such as advanced analytical and computational tools and state-of-the-art diagnostic tools and leading expertise) will be employed to address practical challenges facing the nuclear industry.

2.2.2 Economic Viability

Once scientific research establishes how nuclear power plants will age and aging management programs are identified, operators must demonstrate that the costs associated with continuing to maintain and operate their nuclear power plants are justified and remain in the best interest of their owners. It is likely that as nuclear power plants operate beyond their original license periods, significant component replacements will become necessary, thereby increasing costs. Each utility will need to be able to accurately predict such costs in order to make sound business decisions regarding continued long-term plant operation.

Technology, in combination with effective plant management programs, is expected to support new opportunities for further cost savings in areas such as aging management, information technologies, operations and maintenance, training, fuel design, and management. Some of these cost improvements will be within the scope of a regulatory license renewal process (e.g., reactor pressure boundary materials issues), while others may be important to continued economic viability but not have regulatory significance. Safety and economic viability are considered complementary goals. Developed properly, programs that enhance economics also are likely to benefit plant safety.

2.3 Implementing Strategy

Three diverse, yet interrelated sequential strategies will be implemented in the program:

1. Develop the scientific basis to understand, predict, and measure changes in materials and SSCs as they age in environments associated with continued long-term operation of existing LWRs

2. Apply this fundamental knowledge in collaborative public-private and international partnerships, developing and demonstrating methods and technologies that support safe and economical long-term operation of existing LWRs

3. Identify and verify the efficacy of new technology to address obsolescence while enhancing plant performance and safety.

Because of the scale, cost, and time horizons involved in sustaining the current operating fleet of LWRs, achieving the strategic goals of the LWRS R&D Program will require extensive collaboration with the industry, NRC, and international R&D institutions of extensive technical expertise. In addition, recognizing the need to support education and training of the next generation of scientists and engineers, the following strategic guidelines were established to guide organization and implementation of the program:

- Leverage institutional knowledge and collaborative opportunities between the nuclear industry, national laboratories, universities, and the federal government in developing the basic scientific understanding in predicting key materials and safety margin characterizations

- Using the LWRS R&D Program vision and goals, build relationships across established relevant research interests, both at international and domestic levels

- Integrate Nuclear Energy University Program projects with selected R&D pathways

- Ensure the LWRS R&D Program is accountable to sponsors, partners, and other stakeholders.

The 60-year lifetime license for the first group of nuclear power plants will expire between the years 2029 and 2039. The LWRS R&D Program can be divided into four sequential, yet interconnected, phases that correspond to the four phases of sustainability (Section 1.2). The following describes the main objectives of each phase and the timeframe applicable to those nuclear power plants with the 60-year license expiring in 2029 and beyond:

- Phase I: Build confidence for the industry to proceed with 80-year license renewal, using data and tools (the timeframe for this phase is 2010 to 2015)

- Phase II: Enable the industry to make the decision to invest in plant refurbishments, modernizations, and licenses for 80-year operations (the timeframe for this period is 2015 to 2020)

- Phase III: Apply scientific solutions and continuing technology development to support NRC review and plant capital investment (the timeframe for this period is 2020 to 2030)

- Phase IV: Enable safe and economic operations with the 80-year license (the timeframe for this phase is 2030 and beyond).

On a more abstract level, this program can be broken into the following two periods:

1. Period of license application and review for 80-year operation (Phases I, II, and III fall into this period)
2. Period during which the nuclear power plant fleet operates beyond 60 years of life (Phase IV falls into this period).

The implementation schedule (Figure 2-1) is structured to support the following high-level milestones:

- 2010: Ensure that long-term operation is an accepted high priority option for power generation by industry, DOE, and NRC
- 2015: Build confidence in long-term operation with data and tools
- 2020: Enable industry decision to invest and license for long-term operation
- 2025: Acceptance of advanced tools, methods, and technologies
- 2030: Commence licensed long-term operations.

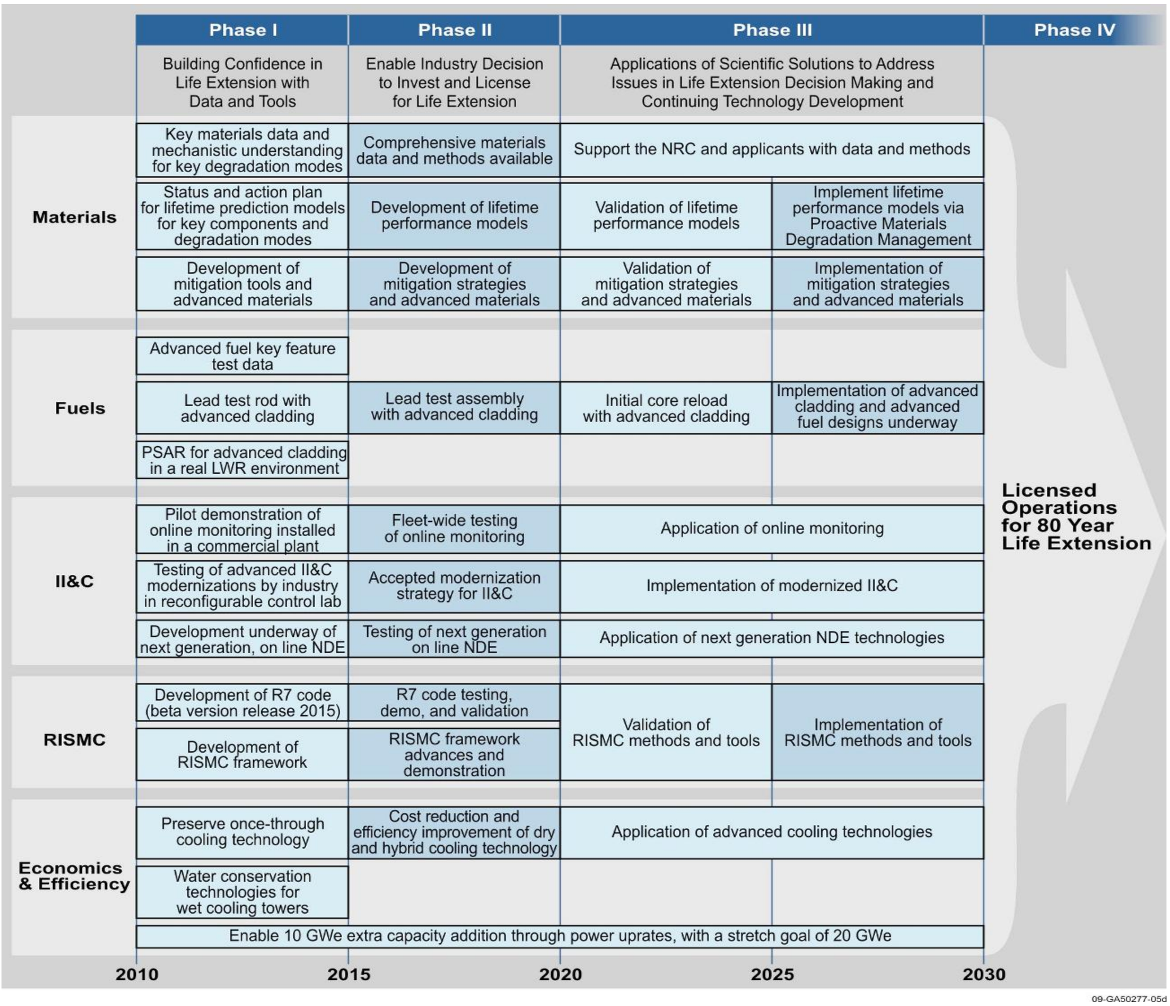


Figure 2-1. Program implementation schedule.

3. RESEARCH AND DEVELOPMENT PATHWAYS

Safety is a fundamental requirement for reliable economic operation; therefore, most of the knowledge and methodologies developed in this program are expected to serve the regulator and the utility. This commonality is a key consideration in defining the R&D pathways and individual R&D projects. The LWRS R&D Program currently is comprised of the following five principal R&D pathways, each of which focuses on a key technical element that ensures the safe, economic, and reliable operation of the existing nuclear power plant fleet:

1. Nuclear Materials Aging and Degradation

2. Advanced LWR Nuclear Fuel Development

3. Advanced Instrumentation, Information, and Control Systems Technologies

4. Risk-Informed Safety Margin Characterization

5. Economics and Efficiency Improvement.

The objective of these R&D pathways is to create a greater level of safety through application of increased knowledge and an enhanced economic understanding of nuclear power plant operational risk beyond the first license extension period. These R&D pathways also provide possible solutions to future challenges and will ensure safe and economic extended nuclear power plant operation.

3.1 Nuclear Materials Aging and Degradation

3.1.1 Background and Introduction

Nuclear reactors present a very harsh environment for components service. Components within a reactor core must tolerate high temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to reduced performance, and in some cases, sudden failure.

Materials degradation in a nuclear power plant is extremely complex due to the various materials, environmental conditions, and stress states. Over 25 different metal alloys can be found within the primary and secondary systems; additional materials exist in concrete, the containment vessel, instrumentation and control equipment, cabling, buried piping, and other support facilities. Dominant forms of degradation may vary greatly between different SSCs in the reactor and can have an important role in the safe and efficient operation of a nuclear power plant. When this diverse set of materials is placed in a complex and harsh environment, coupled with load and degradation over an extended life, an accurate estimate of the changing material behaviors and lifetime is complicated. A small sampling of these metals for a pressurized water reactor is shown in Figure 3-1.

Clearly, materials degradation will impact reactor reliability, availability, and, potentially, safe operation. Routine surveillance and component replacement can mitigate these factors; however, failures still occur. With reactor life extensions up to 60 years or beyond and power uprates, many components must tolerate more demanding reactor environments for even longer times. This may increase susceptibility to degradation for different components and may introduce new degradation modes. While all components (except perhaps the reactor pressure vessel) can be replaced, it may not be economically favorable. Therefore, understanding, controlling, and mitigating materials degradation processes and a technical basis for long-range planning for necessary replacements are key priorities for reactor operation, power uprate considerations, and life extensions. Appendix A contains detailed information on research tasks for nuclear materials aging and degradation.

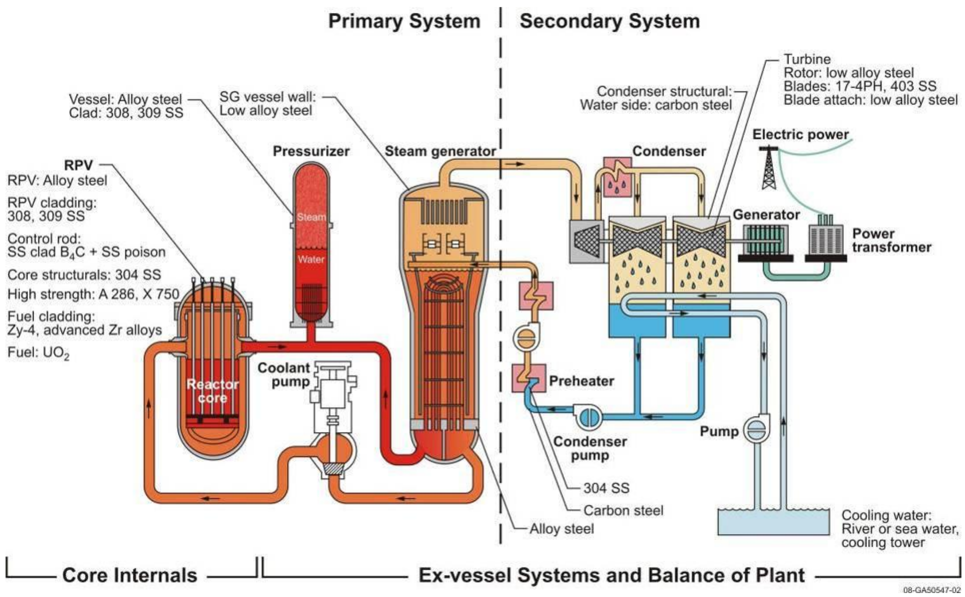


Figure 3-1. Light water reactor metals.

3.1.2 Vision and Goals

Materials research provides an important foundation for licensing and managing the long-term, safe, and economical operation of nuclear power plants. Aging mechanisms and their influence on nuclear power plant SSCs are predictable with sufficient confidence to support planning, investment, and licensing for necessary component repair, replacement, and relicensing. Understanding, controlling, and mitigating materials degradation processes are key priorities. While our knowledge of degradation and surveillance techniques are vastly improved, unexpected degradation can still occur. Proactive management is essential to help ensure that any degradation from long-term operation of nuclear power plants does not affect the public’s confidence in the safety and reliability of those nuclear power plants.

The strategic goals of the Nuclear Materials Aging and Degradation R&D pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations.

Specific outputs from this pathway will include improved mechanistic understanding of key degradation modes and sufficient experimental data to provide and validate operational limits and development of advanced mitigation techniques to provide improved performance, reliability, and economics. Mechanistic and operational data also will be used to develop performance models for key material systems and components in later years.

3.1.3 Highlights of Research and Development

The Nuclear Materials Aging and Degradation R&D pathway activities have been organized into five areas: (1) reactor metals, (2) concrete, (3) cable aging, (4) buried piping, and (5) mitigation strategies. These research areas cover material degradation in SSCs that were designed for service without replacement throughout the life of the plant. Management of long-term operation of these components can be difficult and expensive. As nuclear power plant licensees seek approval for extended operation, the way in which these materials age beyond 60 years will need to be evaluated and their capabilities reassessed in order to ensure that they maintain the required design functions safely and economically. In addition to the five research areas, a Materials Aging and Degradation Assessment also will be conducted to provide a comprehensive assessment of materials degradation.

3.1.3.1 Reactor Metals. Numerous types of metal alloys can be found throughout the primary and secondary systems. Some of these materials, particularly the reactor internals, are exposed to high temperatures, water, and neutron flux. This creates degradation mechanisms that may be unique or environmentally exacerbated. Research programs in this area will provide a foundation upon which a safe regulatory environment can be established for life beyond 60 years. The following eight activities will encompass the reactor metals area (see Appendix A for detailed information about the activities):

- Mechanisms of irradiation-assisted stress corrosion cracking in stainless steels
- High-fluence effects on reactor pressure vessel steels
- Crack initiation in Ni-alloys
- High-fluence effects on irradiation-assisted stress corrosion cracking of stainless steels
- Irradiation-assisted stress corrosion cracking of alloy X-750
- Evaluation of swelling effects in high-fluence core internals
- Irradiation-induced phase transformations in high-fluence core internals
- Surrogate and attenuation effects on reactor pressure vessel steels.

3.1.3.2 *Concrete.* Currently, there is little or no data on long-term concrete performance in nuclear power plants. Long-term stability and performance of concrete structures within a nuclear power plant is a concern. The objective of this task is to assess the long-term performance of concrete. Research task evaluation and prioritization will be performed on an ongoing basis. Plans for research will continue to be evaluated by collaborators at EPRI and NRC to ensure complementary and cooperative research. In addition, formation of an Extended Service Materials Working Group will provide a valuable resource for additional and diverse input.

3.1.3.3 Cabling. Cable aging is a concern that currently faces the operators of existing nuclear power plants. Utility companies carry out periodic cable inspections using nondestructive examination techniques to measure degradation and determine when replacement is needed. Degradation of these cables is primarily caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater.

3.1.3.4 Buried Piping. Maintaining the many miles of buried piping is an area of concern when evaluating the feasibility of continued plant life. While much of the buried pipes comprise either secondary plant or other non-safety-related cooling systems, some buried piping serves a direct safety function. Maintaining the integrity and reliability of all of these systems is necessary for continued plant operation. These systems must be maintained to ensure predictable plant operation and to maintain plant efficiency.

3.1.3.5 Mitigation Technologies. Welding is widely used for component repair. Weld-repair techniques must be resistant to long-term degradation mechanisms. Extended lifetimes and increased repair frequency welds must be resistant to corrosion, irradiation, and other forms of degradation. The purpose of this research area is to develop new techniques for weldments, weld analysis, and weld repair. A critical assessment of the most advanced methods and their viability for LWR repair weld applications is needed.

3.1.3.6 Integrated Research Activities. This research element includes (1) international collaboration to conduct coordinated research with international institutions such as the Materials Aging Institute in order to provide more collaboration and cost sharing, (2) coordinated irradiation experiments to provide a single integrated effort for irradiation experiments, (3) advanced characterization tools to increase materials testing capability, improve quality, and develop new methods for materials testing, and (4) additional research tasks based on results and assessments of current research activities (see Appendix A for more details on these research activities).

3.1.4 Products and Implementation Plan

The main products from the Nuclear Materials Aging and Degradation R&D pathway are (1) mechanistic understanding of key degradation modes, (2) lifetime performance models, (3) advanced mitigation strategies, and (4) advanced replacement materials. The implementation schedule shown in Figure 3-2 is structured to support the following high-level milestones:

- 2010:
    - Complete the first iteration of reactor material degradation matrix
    - Identify the status and potential magnitude of key degradation modes for materials systems and issues.
- 2015:
    - Develop materials data and mechanistic understanding for key degradation modes in hand:
        - Determination of mechanisms of stress corrosion cracking underway
        - Bounding data for reactor pressure vessel embrittlement
        - Concrete degradation
        - Cabling
    - Develop status and action plan for lifetime prediction models for key components and degradation modes
    - Develop mitigation tools and advanced materials options underway:
        - Validation of post-irradiation annealing

– Development of advanced replacement materials.

- 2020:

  - Ensure materials data and methods are available to support high confidence of successful operation to 80 years and predictable service times (replacement times) for major components

    – Validation of lifetime performance models

    – Development of mitigation strategies.

- 2025: Support applicants and NRC with data and methods for materials degradation issues and limitations via proactive materials degradation management.

- 2030: Implement lifetime performance models, mitigation strategies, and advanced replacement materials.

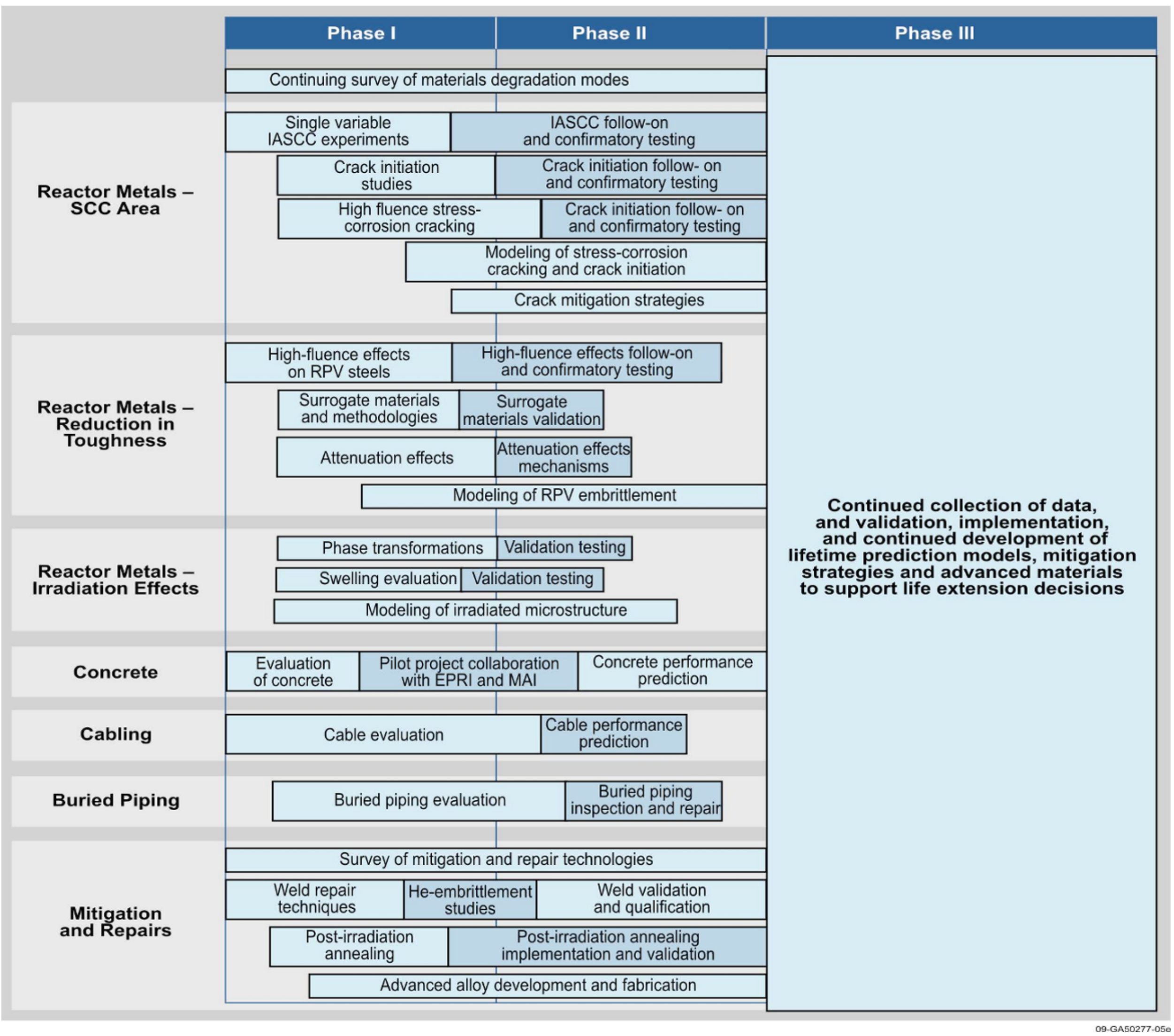


Figure 3-2. Nuclear Materials Aging and Degradation pathway implementation schedule.

3.2 Advanced Light Water Reactor Nuclear Fuel Development

3.2.1 Background and Introduction

Nuclear fuel performance is a significant driver of nuclear power plant operational performance, safety, operating economics, and waste disposal requirements. Over the past two decades, the nuclear power industry has improved plant capacity factors with incremental improvements in fuel reliability and use or "burnup." However, these upgrades are reaching their maximum achievable impact within the constraints of existing fuel design, materials, licensing, and enrichment limits. Although the development, testing, and licensing cycle for new fuel designs is typically long (about 10 years from conception through utility acceptance), these improvements are often used with only an empirical understanding of the fundamental phenomena limiting their long-term performance.

Continued development of high-performance nuclear fuels through fundamental research focused on common aging issues can enable plant operators to extend plant operating cycles and enhance the safety margins, performance, and productivity of existing nuclear power plants. The Advanced LWR Nuclear Fuel Development R&D pathway performs research on improving reactor core power density, increasing fuel burnups, advanced cladding, and developing enhanced computational models to predict fuel performance. This research is further designed to demonstrate each of these technology advancements while satisfying all safety and regulatory limits through rigorous testing and analysis.

To achieve significant fuel cost and use improvements while remaining within safety boundaries, significant steps beyond incremental improvements in the current generation of nuclear fuel are required. Fundamental improvements are required in the areas of nuclear fuel composition and performance, cladding integrity, and the fuel/cladding interaction to reach the next levels of nuclear fuel development. These technological improvements are likely to take the form of revolutionary cladding materials, enhanced fuel mechanical designs, and alternate isotope fuel compositions. As such, these changes are expected to have substantial beneficial improvements in nuclear power plant economics, operation, and safety.

3.2.2 Vision and Goals

Advanced, high-performance fuels are an essential part of the safe, economic operation of LWRs. New fuels have improved safety margins and economics and are more reliable. Fuel provides head-room for additional power uprates and high burnup limits. The scientific basis for fuel performance is well understood, and its response to changing operational conditions and transients is predictable, which supports continuous improvements to reliability and operational flexibility for the nuclear power plant fleet.

Strategic goals are to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants, and apply this information to development of high-performance, high burnup fuels with improved safety, cladding, integrity, and nuclear fuel cycle economics.

3.2.3 Highlights of Research and Development

The Advanced Nuclear Fuels Development Program element is separated into three R&D tasks: advanced design and concepts, mechanistic understanding of fuel behavior, and advanced tools. These tasks were selected to balance development of new knowledge, verifying developed knowledge, and creation of new advanced fuel technology. The scope of the pathway includes all aspects important to fuel design and performance, including fuel design, exposure effects, and cladding material performance and development. Figure 3-3 shows a typical pressurized water reactor fuel assembly. A boiling water reactor assembly is of different design; however, the fuel rods are quite similar.

3.2.3.1 ***Advanced Designs and Concepts.*** The purpose of this task area is to increase the understanding of advanced fuel design concepts, including use of new cladding materials, increases to fuel lifetime, and expansions to the allowable fuel performance envelope. These improvements will allow the fuel performance related plant operating limits to be optimized in areas such as operating temperatures, power densities, power ramp rates, and coolant chemistry. Accomplishing these goals leads to improved operating safety margins and improved economic benefits. Detailed information on the Advanced Designs and Concepts task can be found in Appendix B.

3.2.3.2 ***Mechanistic Understanding of Fuel Behavior.*** This task area will involve testing and modeling of specific aspects of LWR fuel, cladding, and coolant behavior. Examples include pellet cladding interaction, fission gas release, coolant chemistry effects on corrosion, and crud (oxide) formation. Improved understanding of fuel behavior can be used in fuel design, licensing, and performance prediction.

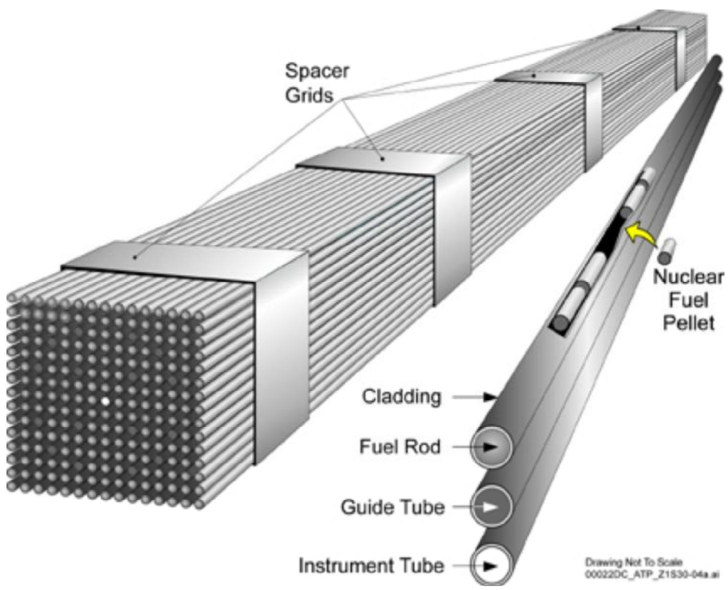


Figure 3-3. Nuclear fuel assembly.

An improved fundamental understanding of phenomena that impose limitations on fuel performance will allow fuel designers, fabricators, plant chemists, and code developers to optimize the performance of current fuels and the designs of advanced fuel concepts. A life-cycle concept will be applied so that optimization will be applied to fabrication, in-reactor use, and performance as spent fuel in storage. Fundamental mechanistic models will provide a foundation for supporting the LWRS R&D Program strategic objectives in developing advanced fuels. The following models will be included in this task (see Appendix B for detailed information about the following models):

1. Fuel mechanical property change model as a function of exposure

2. Pellet cladding interaction model development

3. Chemistry coolant model development

4. Mesoscale models of microstructure fuel behavior

5. Hydrogen uptake behavior of Zr cladding.

3.2.3.3 Advanced Tools. This task area will use increased understanding of specific fuel performance phenomena that will be integrated into encompassing fuel performance advanced tools. These advanced tools, including modeling and simulation codes, advanced experimental capabilities, and real-time performance monitoring, will be developed to enhance plant and repository efficiency. In addition, the advanced tools developed will be used to minimize the time required to realize the gains made through this R&D effort by decreasing the amount of time needed for materials development and fuel qualification. The following activities will be included in this task (see Appendix B for detailed information about the following activities):

1. Engineering design and safety analysis tool

2. Mechanical models of composite cladding

3. Irradiation design studies of advanced silicon carbide (SiC) cladding

4. Experimental campaign to verify design and safety margin calculation tool

5. Advanced mathematical tools to support advanced nuclear fuels calculations.

3.2.4 Products and Implementation Plan

The main product produced from this pathway is development of SiC/silicon carbide fiber (reinforced) (SiC/SiC_f) fuel cladding. This activity allows direct product development and development of the supporting enabling technology and understanding required to design and license a new generation of fuel. Without the specific SiC/SiC_f cladding development, another high value fuel development activity would be used to focus fuel development activities toward the roll out of a specific product. The implementation schedule shown in Figure 3-4 is structured to support the following high-level milestones:

- 2010:
  - Design and planning of SiC/SiCf rodlet irradiation campaign
  - Rodlet testing planning/design with SiC
  - Rodlet irradiation with SiC
  - Mechanical modeling of SiC/SiCf matrix
  - Licensing case for SiC applications in commercial applications
  - Out-of-core testing, repeated stress, thermal cycles, and failure modes for SiC.
- 2015:
  - Initial lead test rod design with SiC and planning
  - Rod testing planning/design with SiC
  - Rod irradiation with SiC.
- 2020:
  - Initial SiC lead test assembly licensing
  - Reload testing planning/design with SiC

- Reload irradiation with SiC.

- 2025:
  - Initial SiC reload design
  - Initial core reload with SiC
  - Irradiation program for increased enrichment bundles
  - Irradiation program for increased exposure bundles.
- 2030:
  - Fleetwide implementation of SiC reload and advanced fuel designs under way
  - Lead test assembly for increased enrichment fuel
  - Lead test assembly for increased exposure fuel.
- 2040:
  - Advanced fuel designs
  - Advanced uprated cores using SiC cores.

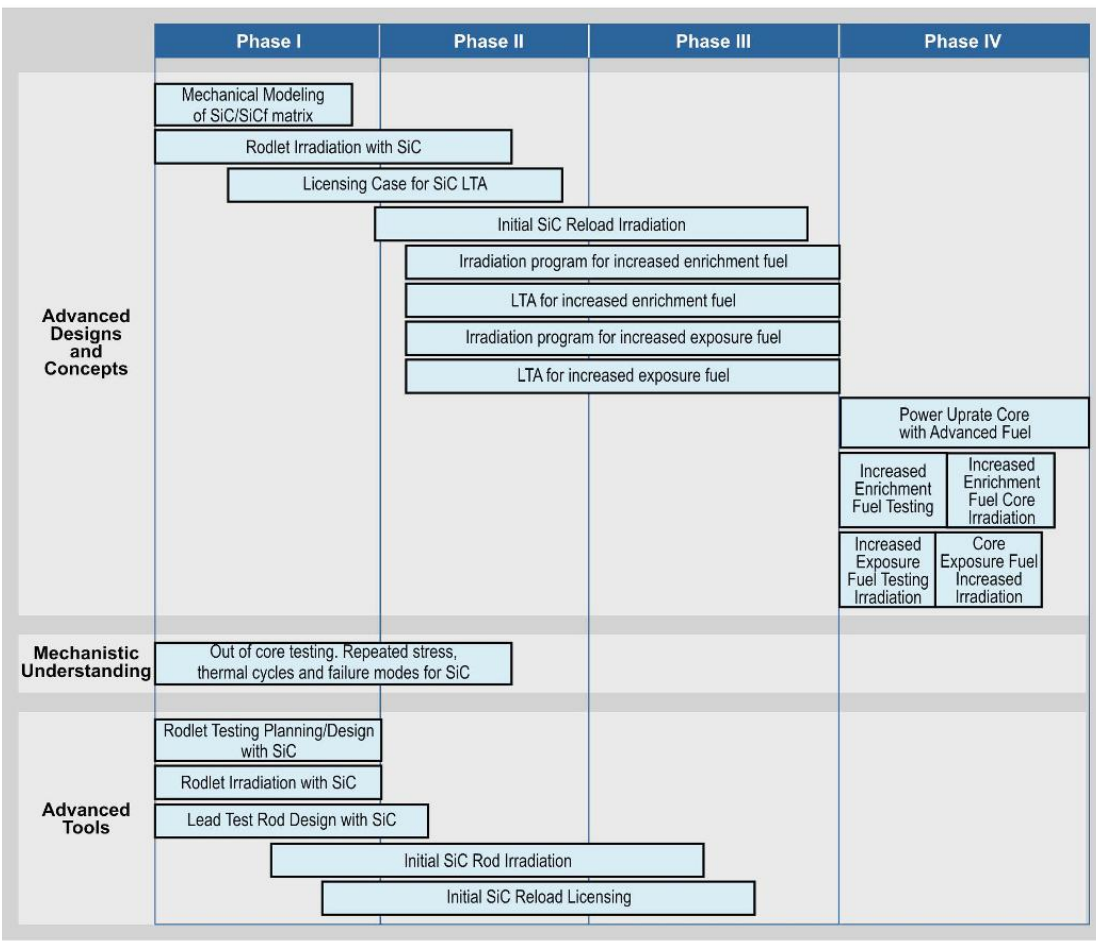


Figure 3-4. Advanced Light Water Reactor Nuclear Fuels Development pathway implementation schedule.

3.3 Advanced Instrumentation, Information, and Control Systems Technologies

3.3.1 Background and Introduction

Instrumentation, information, and control (II&C) systems technologies are essential to ensuring delivery and effective operation of nuclear power systems. They are enabling technologies that affect every aspect of nuclear power plant and secondary plant operations – analogous to a central nervous system. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital instrumentation and control systems in nuclear power plants. Their findings identify the need for new II&C technology integration. Unfortunately, this report, issued in 1997, still reflects the current state of affairs at nuclear power plants. Numerous issues that must be addressed in order to implement new types of II&C systems in commercial nuclear power plants have not been satisfactorily demonstrated in the commercial nuclear power industry of the United States. Without new types of II&C systems, today's nuclear power plants II&C systems will become antiquated and unreliable, unfamiliar to a future workforce, and a liability on the corporate balance sheet.

Digital II&C technologies are deployed in a number of power generation settings worldwide. The situation in the United States nuclear power sector differs from these other settings in several key respects: analog systems that have been operated beyond their intended service lifetimes dominate II&C systems in place today; regulatory uncertainty and associated business risk concerns are dominant contributors to the status quo; and current utility business models have not evolved to take full advantage of digital technologies to achieve performance gains. As a consequence, digital technologies are implemented as point solutions to performance and obsolescence concerns with individual II&C components. This reactive approach is characterized by planning horizons that are short and typically only allow for 'like-for-like' replacements to be made. This results in a fragmented, non-optimized approach that is driven by immediate needs. As a long-term strategy, this is not sustainable in light of the evolution of II&C technology, availability of skills needed to maintain this antiquated technology, and high costs and uncertainties associated with doing so.

In addition to some of the technical challenges and associated R&D needs, in order to be successful in supporting long-term operational goals, a different approach is needed to technology development and deployment. These must be recognized in light of current industry trends and factors. The first is that the nuclear power generation sector is rarely an early adopter of new II&C technologies. Consequently, the nuclear power industry does not drive the development of II&C technology needs or availability in the power generation sector as a whole. Rather, it reacts to developments implemented in other sectors of power generation and implements them some time after others. Second, digital technologies are deployed on an as-needed basis to replace failing analog devices that are no longer maintainable. Figure 3-5 shows a contemporary control room at a nuclear power plant that relies on analog instrumentation and controls that require extensive procedures and highly trained operators. Because these technologies replace like-for-like capability – analog with digital –

Figure 3-5. A contemporary control room at a nuclear power plant.

the planning horizon for such activities is typically short, which tends to marginalize the potential benefits that can be achieved through digital II&C technology development and deployment (see Appendix C for more detailed information).

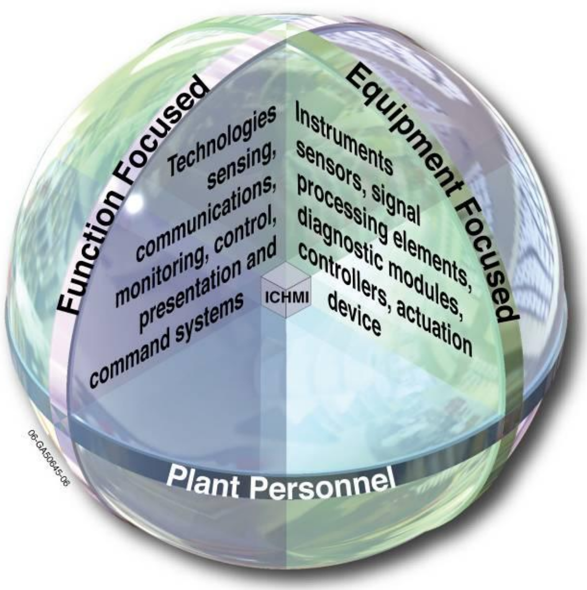
Individual force-fitting approaches to digital technology deployment and ever increasing obsolescence, long-term safety, and reliability of analog devices necessitate reconsideration of potential solutions involving digital technologies for nuclear energy systems. This reconsideration must include the long-term issues associated with monitoring and managing aging and degradation of plant systems and initiatives that must be undertaken to ensure long-term sustainability of II&C systems in a way that achieves availability of a cost-competitive, reliable nuclear energy supply.

A technology-driven approach in this R&D area alone will be insufficient to yield the type of transformation that is needed to secure a long-term source of nuclear energy base load; a new approach is needed. An effective R&D initiative must engage the perspectives of stakeholders (i.e., asset owners, regulators, vendors, and R&D organizations) in order to articulate and initiate relevant R&D activities.

3.3.2 Vision and Goals

Maintaining the reliability and safety of II&C systems used for process measurement and control is crucial in meeting the licensing basis of nuclear power generation assets. Aging and obsolescence of the installed technologies is a continuing concern for asset owners. Advances are needed to support crucial characterization and monitoring activities that will become increasingly important as materials age. The aim of collaborations, demonstrations, and approaches envisioned by this pathway are intended to lessen the inertia that sustains the current status quo of today's II&C systems technology and to motivate transformational change and a shift in strategy – informed by business objectives – to a long-term approach to II&C modernization that is more sustainable.

One of the goals of this program is to ensure the issues do not become a limiting factor in the decisions on long-term operation of these assets. Goals for technology introduction are to enhance efficiency, safety, and reliability; improve characterizations of the performance and capabilities of passive and active components during periods of extended operation; and to facilitate introduction of other advanced II&C systems technologies by reducing regulatory uncertainties. The R&D activities of this program are intended to set the agenda for a long-term vision of future operations, including fleetwide integration of new technologies.



3.3.3 Highlights of Research and Development

A program element of R&D activities is proposed to develop some of the needed critical capabilities of digital technologies to support long-term nuclear asset operations and management. This includes comprehensive programs intended to do the following:

- Develop national capabilities at the university and laboratory level to support R&D

- Create or renew infrastructure needed for long-term research, education, and testing
- Support creation of new technologies that can be deployed to address the sustainability of today's II&C systems technologies
- Improve understanding of, confidence in, and facilitate transition to these new technologies
- Support development of the technical basis needed to achieve technology deployments.

3.3.3.1 ***Centralized Online Monitoring and Information Integration.*** As nuclear power systems begin to be operated during periods longer than originally anticipated, the need arises for more and better types of monitoring of material and system performance. This includes the need to move from periodic, manual assessments and surveillances of physical systems to online condition monitoring. This represents an important transformational step in the management of physical assets. It enables real-time assessment and monitoring of physical systems and better management of active components based on their actual performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions about asset management and safety management.

3.3.3.2 ***New Instrumentation and Control and Human System Interface Capabilities.*** R&D activities are aimed at the eventual modernization of II&C systems technologies used in nuclear energy production. Asset owners and regulators view these as enabling in the dialogue of long-term asset and safety management. The evidence of aged and obsolete technologies is abundant in the control centers of nuclear power plants. The analogy of control rooms as the tip of the iceberg for aging analog technology is particularly apt because it typifies both the problem and a substantial opportunity for R&D to impact systems on a plant scale much larger than what can be readily observed.

Through long-term collaborations with leading international research institutes and capitalizing on new national capabilities for simulation-based technology development and testing, research in visualization, process control, and automation is planned. The long-term objectives of these research activities are to demonstrate new concepts of operations for nuclear power generation assets that address the need for technology modernization, improved state awareness, improved safety, and optimized asset management. These objectives will be achieved by a series of multiyear pilot programs aimed at developing and demonstrating new technologies and concepts for information and control technologies, including the following:

1. Advanced instrumentation and information pilot projects
2. Future concept of operations pilot projects
3. Advanced automation pilot projects.

3.3.3.3 ***Nondestructive Examination Technologies.*** Activities are proposed to develop and test sensors and characterization methods and technologies for a range of nondestructive examination applications. Working closely with the Nuclear Materials Aging and Degradation R&D pathway, this pathway will develop sensors and accompanying technologies to detect and characterize the condition of material parameters needed to assess the performance of SSC materials during long-term operation, including sensors for measuring material properties to derive parameter estimates of specific aging and performance features and analytic capabilities and methods for characterizing the state and condition of material properties in order to obtain 'diagnostic' accuracy about material aging and degradation. This will provide the ability to move from identification of damage and incipient change to more precise descriptions about the underlying mechanisms of change, their progression in materials, and a description of the specific transformations that affect a material or system's ability to achieve its design function.

Activities also are proposed to build on sensors, characterization, and more refined diagnostics to enable prognostic assessments of materials and performance to be made. These capabilities will aid in answering the 'so what' types of questions that arise in connection with material assessments. This entails extending our knowledge and models of materials and material change processes to include predictions about the eventual consequences of change. This requires the need to incorporate information from material science studies and from other R&D pathways and research programs, including international consortia, to develop interim prognostic models that can be validated and improved through bench scale, engineering scale, and accelerated testing to yield models for predicting the effects of different aging mechanisms and associated phenomena.

3.3.3.4 ***Regulatory Engagement.*** Ongoing working group activities between the staff of NRC and the nuclear power industry on digital technologies for advanced LWR design submittals underscore the need for a process of engagement within this pathway. Research results and data are needed that can be used for establishment of a regulatory technical basis to support rulemaking and reviews and to provide necessary confidence in the tailored application of these technologies for asset owners. This program includes a specific engagement activity to support interactions with the regulator in order to derive the greatest benefit from these research activities and to achieve goals for eventual deployments.

3.3.3.5 ***Industry Working Groups.*** Nuclear asset owner engagement is a necessary and enabling activity to obtain data and accurate characterization of long-term operational challenges, assess suitability of proposed research for addressing long-term needs, and gain access to data and representative infrastructure needed to assure success of the proposed R&D activities.

3.3.4 Products and Implementation Plan

The main products of the Advanced II&C Systems Technologies R&D pathway are as follows:

- Technologies for and demonstrations of highly integrated control and display technologies that address long-term objectives of nuclear power plant operation, including the following:
    - Fleetwide management of asset information to support integrated operations
    - Improved visualization and use of information to support decision making and actions
    - Greater automation of functions and availability of operator support systems to improve efficiencies and reduce errors
- Online monitoring of active and passive components to reduce demands for unnecessary surveillance, testing, and inspection; minimize forced outages; and provide monitoring of physical performance of critical SSCs
- Nondestructive examination technologies for characterizing performance of physical systems in order to monitor and manage the effects of aging on SSCs.

The program activities occur in three phases (see Figure 3-6). Phase I, from FY 2010 to FY 2015, R&D activities are intended to create technologies with new functional capabilities. The objectives of this phase are to create and demonstrate new capabilities to achieve the objectives and vision of long-term asset operation. Phase II, from FY 2016 to FY 2020, R&D activities will create more mature technologies that are capable of some field deployments, pilot projects with asset owners, and consortia. Phase III, from FY 2021 to FY 2029, the technology maturity and success with initial deployments will lead to and motivate a shift in the technology base for II&C systems used during long-term operation. Fleet wide deployments and standardization of technology will be ongoing and more R&D activities will lead to greater regulatory engagement and acceptance. Appendix C contains detailed information on the three phases.

Projects	Phase I	Phase II	Phase III
Centralized Online Monitoring	• Algorithm development • Scale studies • Field studies • Industry participation	• Technology maturity • Fleet-wide tests • Industry leadership • Industry standards • License amendments	• Technology standardization • Industry-wide implementation • Regulatory acceptance
New I&C and HSI	• Advanced visualization technology development • System integration concept development • New automation	"First movers" • Individual plant deployment • Industry demonstration	"Modernized Industry" • Fleet-wide deployments • Industry deployment • Standardization
NDE Technologies	• SSC characterization needs defined • Characterization methods and technologies developing	• SSC characterization demonstrated • Characterization methods refinement • License applications using NDE methods	• SSC characterization needs being met • Characterization methods & technologies standard • Industry-wirde and international trending
Advanced I&C Inputs	• Regulatory engagement • Industry participation • International collaboration • University engagement	• Joint regulatory research • Industry working groups and standards bodies • International coordination • University infrastructure	• Integration of R&D with regulatory technical bases • Industry-wide meetings • International standards

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Figure 3-6. Advanced II&C Systems Technologies pathway implementation schedule.

3.4 Risk-Informed Safety Margin Characterization

3.4.1 Background and Introduction

The Risk-Informed Safety Margin Characterization (RISMC) pathway focuses on advancing the state-of-the-art in safety analysis and risk assessment to support decision making on nuclear power plant life extension beyond 60 years. A comprehensive approach involves four questions that need to be addressed and resolved from the risk and safety perspectives (Figure 3-7). With the plant life extension well beyond the originally designed lifetime, the safety questions take on additional significance due to plant aging (namely how plant aging affects our answer to the four questions), and how confident we are about the answers. In

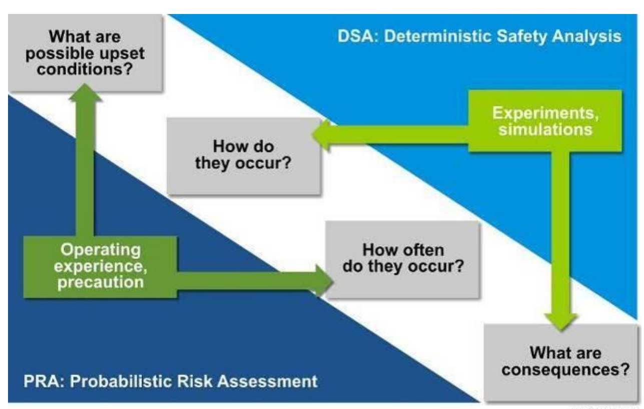

Figure 3-7. Nuclear plant safety analysis.

particular, aging of SSCs has potential to increase frequency of initiating events of certain safety transients; create new sequences associated with previously-not-considered SSC failures; and increase severity of safety transients due to cascading failures of SSCs.

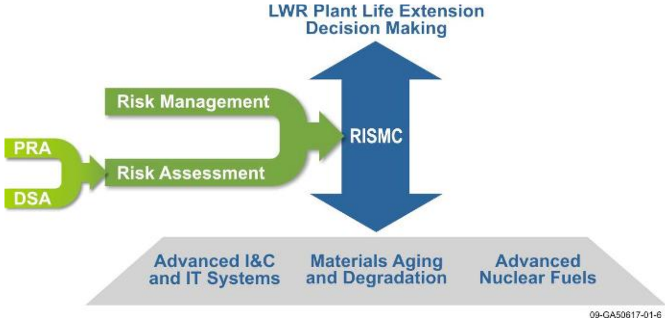

Figure 3-8. RISMC in context of the LWRS R&D Program (PRA = probabilistic risk assessment; DSA = deterministic safety analysis).

The decision on life extension requires us to scrutinize and quantify the uncertainty by which we predict the safety envelope of the aging plant and the efficacy of measures undertaken to manage the aging effect. In this context, the main objective of RISMC R&D is to establish science-based, risk-informed methodology and tools to determine the safety margin envelope with high confidence. Within the LWRS R&D Program, the RISMC pathway provides the bridge from physics and technology-driven pathways to life extension decision-making (Figure 3-8).

The concept of safety margins as a cornerstone in nuclear reactor design emerged during the early days of nuclear power as a part of the defense-in-depth approach to ensuring nuclear safety. Defined as the minimum distance between the system's "loading" and "capacity," safety margin is expressed in terms of safety-significant parameters (e.g., cladding temperature and containment pressure) and determined for a range of anticipated system operating conditions (Figure 3-9). Traditionally, in nuclear power plant design and licensing, availability of safety margins must be demonstrated for a prescribed set of design-basis accidents.

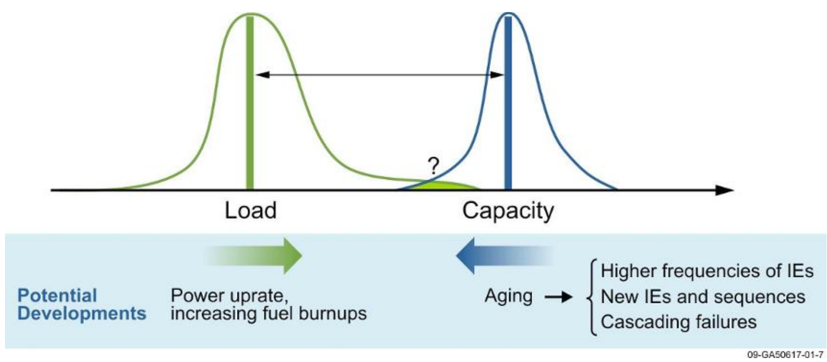

Figure 3-9. Safety margin trend relevant to light water reactor sustainability.

In parallel with a deterministic safety analysis (DSA) approach, probabilistic risk analysis (PRA) methods have been developed and applied to analyze the safety of nuclear power plants. Notably, safety margins calculated by the DSA methods (e.g., accident simulation codes and structural capacity codes) are used to support the specification of "success criteria" in the plant's PRA. Pioneered by the "Reactor Safety Study" (WASH-1400, 1975), the PRA technology has matured and currently provides the nuclear power industry and the regulator with powerful tools to analyze plant safety, identify system vulnerabilities, provide a framework for effective resource allocation, and focus research and plant operations on risk-significant safety threats. (Appendix D provides more information on PRA methods and the DSA approach.)

The state-of-the-art and trends in R&D related to risk-informed safety analysis topics can be viewed in three interrelated groups: (1) advanced PRA techniques, (2) advanced DSA techniques, and (3) methods and tools for analysis integration and visualization of results that support effective decision making. Overarching themes in all three groups are analysis completeness, uncertainty treatment, and computational efficiency.

With respect to methodology for integrated safety assessments, quantification and utilization of plant safety margins and their regulatory implication have received increased attention during recent years, paving way to formulation of RISMC as an R&D area. A comprehensive review of the state-of-the-art and discussion of open issues related to RISMC can be found in the CSNI Safety Margin Action Plan group report, NEA/CSNI/2007(9). Beyond the still-open formidable questions on RISMC framework, it is widely recognized that success of the risk-informed approach requires enhanced simulation tools (computer codes) to enable system analysis with high fidelity and treatment of uncertainties, which can be significant (e.g., in non-design-basis accidents and beyond- design-basis accident situations). These challenges will increase as plant operational life is extended further.

Figure 3-10 depicts technical elements of RISMC in the context of the LWRS R&D Program. In the spirit of defense-in-depth, margin is considered to be significant to the degree that it exceeds uncertainties and variability associated with a given comparison between "load" and "capacity." This idea applies to the success of active functions and passive SSC integrity, which is instrumental to characterization, mechanistic understanding, prediction, and monitoring of the plant aging and degradation behaviors and their impact on plant life extension decision making.

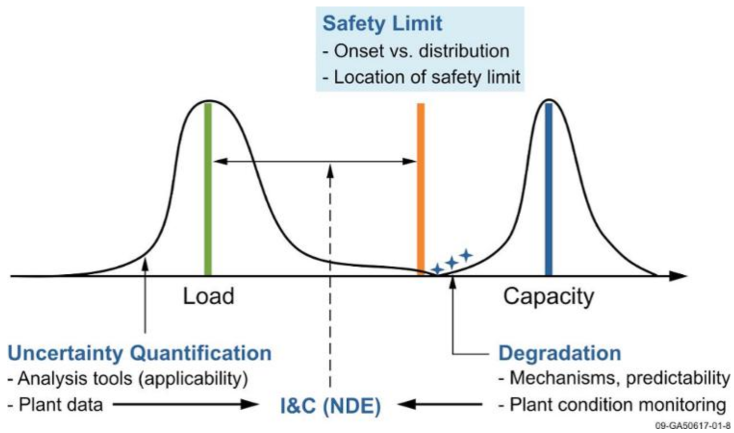

Figure 3-10. Elements of the RISMC model for light water reactor sustainability.

3.4.2 Vision and Goals

Safety is central to design, licensing, operation, and economy of nuclear power plants. As the current LWR nuclear power plants age beyond 60 years, there are possibilities for increasing the frequency of equipment failures that initiate safety-significant events and for creating new failure modes. Accurate characterization of plant safety margins can play an important role in facilitating decision making related to LWRS. In addition, as R&D in the LWRS R&D Program and other collaborative efforts obtain new data and improve scientific understanding of physical processes that govern materials aging and degradation and develop technological advances in nuclear reactor fuels and plant II&C, there are needs and opportunities to manage plant safety, performance, and assets in an optimal way.

Advanced analysis methods and simulation tools for predicting and managing plant response and safety margins are an accepted and essential part of operating and licensing nuclear power plants. Using the science-based models and databases, RISMC provides effective support and guidance to plant operations, maintenance, major components replacement, and plant licensing decisions.

The strategic objectives of the RISMC R&D pathway are to bring together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management. The RISMC research pathway aims to develop an integrated framework and advanced tools for safety assessment that enables more accurate characterization and visualization of the plant's safety margins.

3.4.3 Highlights of Research and Development

The RISMC R&D pathway is driven by recognition that risk-informing plant safety margins present an avenue for enhancing operational flexibility and safety benefits obtained from the transition toward risk-informed and performance-based regulation. Existing methods and tools used today in deterministic and probabilistic safety analysis, by themselves and within the current assessment framework, are not adequate to cost-effectively manage the risk and operability significance of aging of SSC. Therefore, there are conceptual and technical “capability gaps” (in frameworks, tools, and data that need to be filled to enable integrated and defensible decision-making regarding the continued operation of nuclear power plants after their current license terms.

Once matured and established, RISMC developments will benefit LWRS R&D Program objectives by (1) creating a strong technical basis for an enhanced risk-informed regulatory structure that enables optimization of plant operation, inspection, maintenance, and replacement of plant SSCs; (2) enabling effective long-term management of plant resources (for which accurate characterization and prediction of safety margins are a prerequisite); and (3) helping guide R&D planning toward maximum payoff from both resource utilization and risk perspectives.

The RISMC R&D pathway is built on the vision that long-term operation of the existing fleet of nuclear power plants requires continued demonstration of their high-level of performance in plant reliability, safety, and economy, and that such objectives require advanced methods and tools to support analysis of plant safety margins and input into operational decision-making. While RISMC pathway planning does not exclude theoretical considerations and generic developments in a broad context, the programmatic approach is driven by the need to ensure effective use of limited resources to meet the anticipated time window (i.e., 2014 through 2019) for investment decision-making of nuclear power plant operators to support plant life extension beyond 60 years. This narrowing down of focus is necessary to develop necessary methods and tools to address the highest priority issues in a topic as broad as RISMC, which involves the whole domain of PRA, DSA, and their short and long-term developmental needs.

Given the LWRS R&D Program focus, the RISMC R&D pathway devised strategy is shown in Figure 3-11 (the RISMC pathway facilitates integration and visualization of R&D contributions in other pathways on sustainability critical information and sustainability critical analytical tools). Areas marked in light blue (including part of the sustainability critical information and sustainability critical analytical tool boxes) depict the RISMC R&D activity domain). The guiding principle is to focus on developing knowledge/capability to facilitate enhanced decision making and improved regulatory/public acceptance of long-term plant operation. Furthermore, RISMC R&D is envisioned as a mechanism for providing an integrated, science-based framework to enable effective visualization and efficient implementation of advances achieved in the other LWRS R&D pathways.

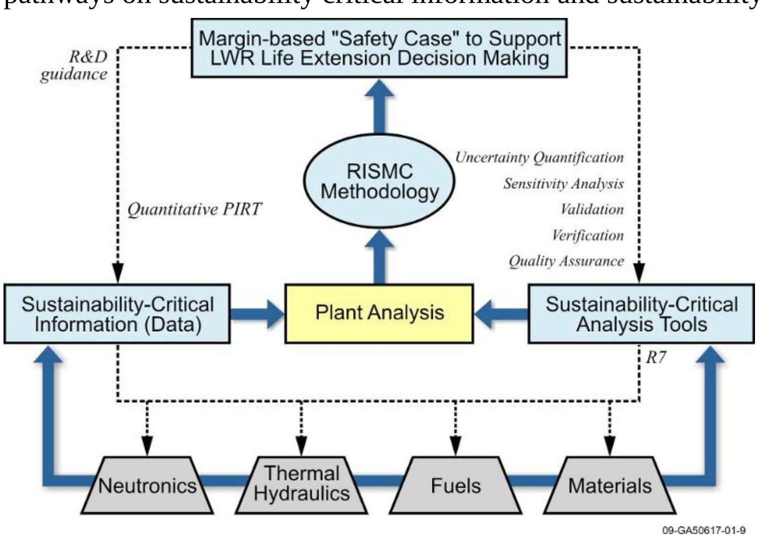

Figure 3-11. Research and development strategy of RISMC for LWR sustainability.

The RISMC study effort in FY 2009 resulted in further clarification of the RISMC concept and formed the basis for the project planning as outlined in Figure 3-12 (see Appendix D for more detailed information on the RISMC R&D pathway).

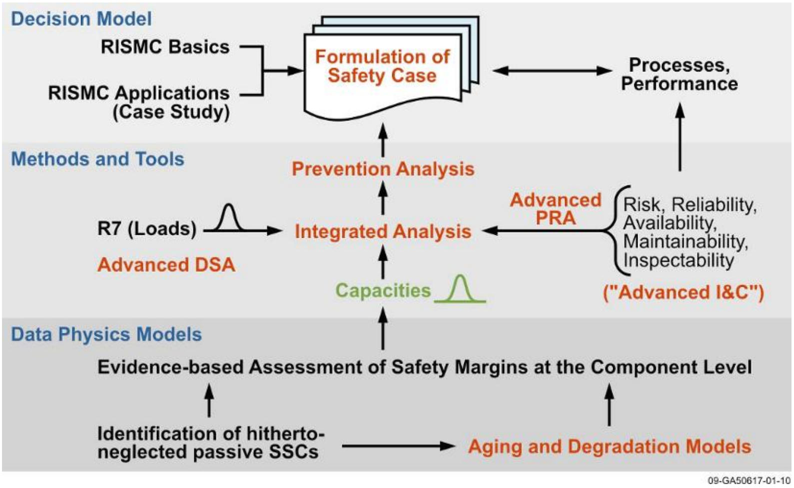

Figure 3-12. RISMC project hierarchy and information flow.

3.4.3.1 RISMC Framework Development. Although LWRs are a mature and successful technology in the United States with an impressive track record in nuclear power plant safety and performance over the past two decades, the next wave of new plant deployment and life extension of the existing operating LWR fleet beyond 60 years is anything but certain. There is broad consensus that technical, cost, and schedule uncertainties in certification and licensing are a significant hindrance to prospective applicants for new licenses, especially for technologies other than LWR. Many discussions tacitly assign a great deal of blame for this to NRC processes.

Part of the traditional approach to licensing is to invest very substantially in margin. The concept of margin has enormous benefits in decision-making, but traditional implementation of the concept has proven to be enormously expensive. A comprehensive set of plausible safety margins will make the sustainability decision easier for both licensees and NRC. Thus, it is important to formulate a margin-based safety case framework aimed at streamlining NRC review and subsequent licensee implementation. The actual technical content of a safety case is necessarily plant-specific; the framework will establish a set of plant-specific technical demonstrations whose integrated presentation to NRC should help to reduce regulatory uncertainty.

Development and demonstration of a new technology-neutral paradigm of science-based safety case development, evaluation, and acceptance will ensure predictable, streamlined, and cost-effective licensing of nuclear installations. It will be achieved through (1) a set of advanced simulation and analysis tools to enable accurate quantification of the system's margins to safety, (2) a formalized (computerized) technology-neutral framework for safety case development, and (3) a knowledge center of previous license applications. A comprehensive, high-quality, and defensible safety analysis submitted by the license applicant is paramount to ensuring the effectiveness of the application's regulatory review.

The proposed research is driven by the idea that reducing uncertainties facing applicants can be achieved not only by working on improved understanding of the technical factors governing particular margins, but by proactively establishing the character and rigor of the portfolio of tests, demonstrations, and commitments to be comprised in the licensing safety case. In the abstract, this idea is not new, but in the United States, previous implementations of it have defaulted to licensing tradition, rather than proactively trying for an improved formulation of the safety case. In short, the proposed task will take up, from a DOE perspective, where NRC left off and identify and address technical issues within the RISMC framework.

3.4.3.2 Technology Integration. This task was formulated with the objective of identifying crosscut case studies that support formulation and demonstration of the RISMC framework for LWRS. The work scope is accomplished largely within the RISMC working group activity.

3.4.3.3 Enabling Methods and Tools. With focus on the effect of plant aging on life extension decision making, characterization of the nuclear power plant safety margin is hindered by large uncertainties that exist in modeling and predicting behaviors of aging SSCs in a broad range of nuclear power plant operating and abnormal conditions and nuclear power plant system dynamics in accident scenarios involving SSC failure modes not studied before. Existing PRA and DSA methods ignore reliability of the plant's passive SSCs and their failure physics, making them unsuited for capturing the essence of aging impact. Of particular interest is identification of catastrophic system degradation scenarios (e.g., cascading failures that cannot be ruled out as "physically unreasonable"). These scenarios require measures (in nuclear power plant inspection, maintenance, and modification) to eliminate system vulnerability. This thrust focuses on advancing the PRA and DSA methods to enable their use in assessing the aging effects on nuclear power plant safety margin.

3.4.3.3.1 Deterministic Safety Analysis—Although incremental advances were made continuously over the past two decades to improve modeling of plant components and transient/accident phenomena, the system (plant) analysis tools used in industry's engineering applications remain based on the decades-old modeling framework and computational methodology that have not taken advantage of modern developments in computer/computational science and engineering. Fundamental limitations in the current generation of system analysis codes are well known to the community. Although the codes have served as an adequate basis to address traditional safety margin analysis, significant enhancements will be necessary to support the challenges of extended and enhanced plant operations.

The new generation of system analysis codes (i.e., R7) provides critical capabilities not available in the legacy codes (e.g., RELAP5), which were developed in the 1970s and were used to analyze design-basis accidents. Notably, enhanced capability for simulation of plant dynamics is central to quantification of safety margins in postulated sequences with aging-induced (new and cascading) failure modes. More broadly, the new DSA capability would help address, in a risk-informed manner, a number of safety and licensing issues facing the nuclear power industry. Together, advanced deterministic and probabilistic modeling capabilities would greatly enable RISMC to the benefit of both the regulator and the nuclear power plant operator.

We envision that the new generation production code will build on the decade-old and tested legacy codes (like RELAP5) while capitalizing on extraordinary advances in computing power and computational science (including computational fluid dynamics, neutron diffusion/transport, and fluid-structure interactions) of the past decades. The high-order accurate schemes, modern software architecture, and rigorous procedures for verification and validation are critical in implementing algorithms for sensitivity analysis and performing uncertainty

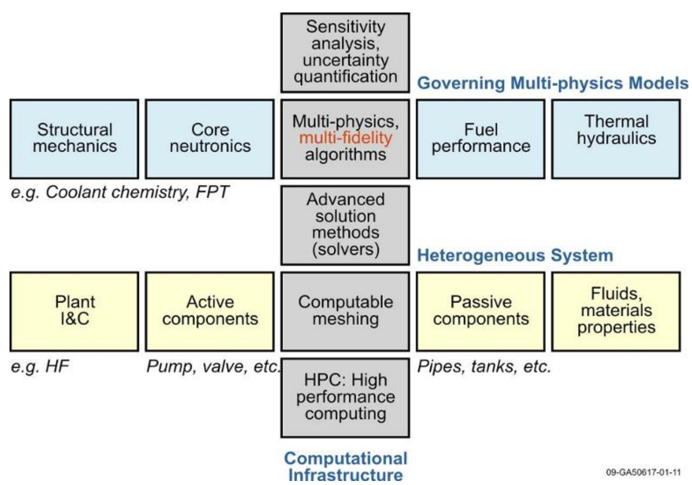

Figure 3-13. Composition of a next-generation production code for nuclear system analysis and safety margin quantification.

quantification, which are essential components to improve understanding and utilization of safety margins (Figure 3-13).

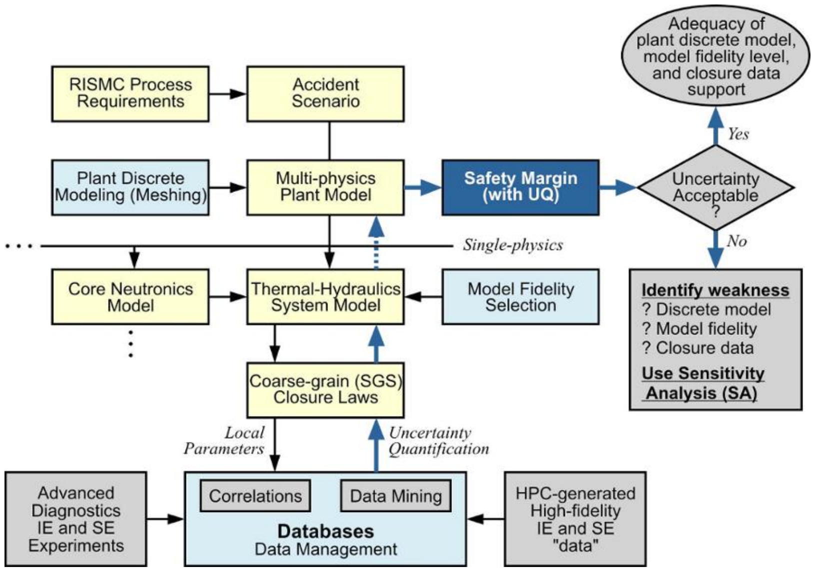

Figure 3-14. Elements of a next generation system code to support the RISMC process.

The new DSA capability would help address, in a risk-informed manner, a number of safety and licensing issues facing the nuclear power industry. Multiphysics coupled treatment offers potential to qualify and improve fidelity of the prediction of safety margins in design-limiting scenarios (Figure 3-14). These same advances and their promulgation in engineering applications would allow identification and quantification of risk-significant transients (both operating and accident sequences), on a scale never before achieved in probabilistic risk analyses. Together, advanced deterministic and probabilistic modeling capabilities would greatly enable RISMC to the benefit of the regulator and the regulated.

3.4.3.3.2 Probabilistic Risk Analysis—Like the state-of-practice thermal hydraulic analysis tools that are still used for licensing, the traditional PRA paradigm was formulated in the mid-1970s to resolve certain issues of that time. It, too, is based on simplifications and approximations that are not adequate to support certain decisions today. Although state-of-practice PRA makes some high-level use of certain thermal hydraulic analyses, the usual coupling between thermal hydraulic and scenario-based risk modeling is nowhere near to being close enough to support evaluation of RIMSC. Efforts to transcend the 1970s PRA paradigm are underway; these efforts incorporate dynamical considerations that are all but suppressed in existing PRAs and try to couple directly to mechanistic codes like RELAP. The RISMC R&D pathway needs this development and needs for it to be formulated in a particular way to support RISMC objectives. Participants in this activity will be chosen in a way that leverages the capabilities other institutions in this area.

The computational situation continues to improve at a rapid rate, and the field of dynamic PRA continues to develop. The present subtask is aimed at joining this development and bringing it to bear within the RISMC framework. The capability will require integration of three major components: (1) the simulation engine itself, (2) an internal facility for decision-making that reflects operational procedures based on the current plant state, and (3) coupling to the mechanistic code(s). In addition to all of the inputs to today's PRA, the RISMC application will require consideration of many passive components that are neglected today.

3.4.3.3.3 Prevention Analysis—Optimal development of a safety case calls for optimal selection of a set of SSCs and associated levels of performance as the backbone of that safety case. Prevention analysis is the name that has been given to one specific way of doing this. Prevention analysis works by driving a risk model backward. Most applications of risk models proceed by estimating SSC performance a priori and using that information to synthesize plant risk for comparison with objectives.

This supports a trial-and-error approach to optimization. In contrast to that approach, prevention analysis starts with a desired top-level safety objective and determines what level of SSC performance would need to be credited in the risk model in order to optimally satisfy that safety objective (in this case, optimality means crediting a complement of equipment that is necessary and sufficient to do the job). The solution to this is not unique; correspondingly, prevention analysis presents the decision-maker with alternative strategies for satisfying top-level objectives. These strategies can be ranked with respect to difficulty and expense of implementation. In short, prevention analysis identifies a complement of nuclear power plant capabilities that, taken together, serve to prevent accidents to the degree specified by the top-level safety objective.

3.4.3.4 Technology Inputs. Apart from specialized application areas (such as seismic PRA), most current PRA methodology takes most passive SSCs for granted because it is believed that these components do not contribute significantly to offsite risk. Within the LWRS R&D Program, it is important to challenge that presumption and to examine whether margin issues could emerge for SSCs whose performance is presently taken for granted.

The point of this task is to incorporate, into risk models, passive SSCs whose performance has previously been taken for granted in PRA, but whose loss of physical margin may need to be analyzed. Ultimately, the risk model that these SSCs are added to is the same risk model to be quantified in the enhanced PRA paradigm described above.

3.4.4 Products and Implementation Plan

The main products of the RISMC R&D pathway are as follows:

- R7 code – A system code for mechanistic description and effective simulation of plant transient behavior under a broad range of upset conditions and sequences of risk importance under life extension operation

- RISMC framework – A comprehensive methodology that brings together advanced modeling, simulation and analysis tools, and relevant data to characterize nuclear power plant safety margins, including the effect of plant aging to support plant life extension decision making

- Enabling methods and tools for advanced PRA and advanced prevention analysis to support life extension decision making.

The implementation schedule (Figure 3-15) is structured to support the following high-level milestones:

- 2010

    - Initiate R&D on technology that potentially transforms safety and economics of operating LWRS

    - Formulation of RIMSC methodology

    - Next generation safety analysis tools and R7 code development.

- 2015

    - Release R7 beta version for testing and validation

- Initiate demo of R7-enabled safety analysis that supports life extension decision.

- 2020
  - High confidence and acceptance by industry and NRC for RISMC process and tools to support power uprate and long-term operations evaluations.
- 2025
  - Validation of RISMC methods and tools for life extension applications.
- 2030
  - Industry's broad implementation of RISMC to support plant life extension licensing and enhanced performance.

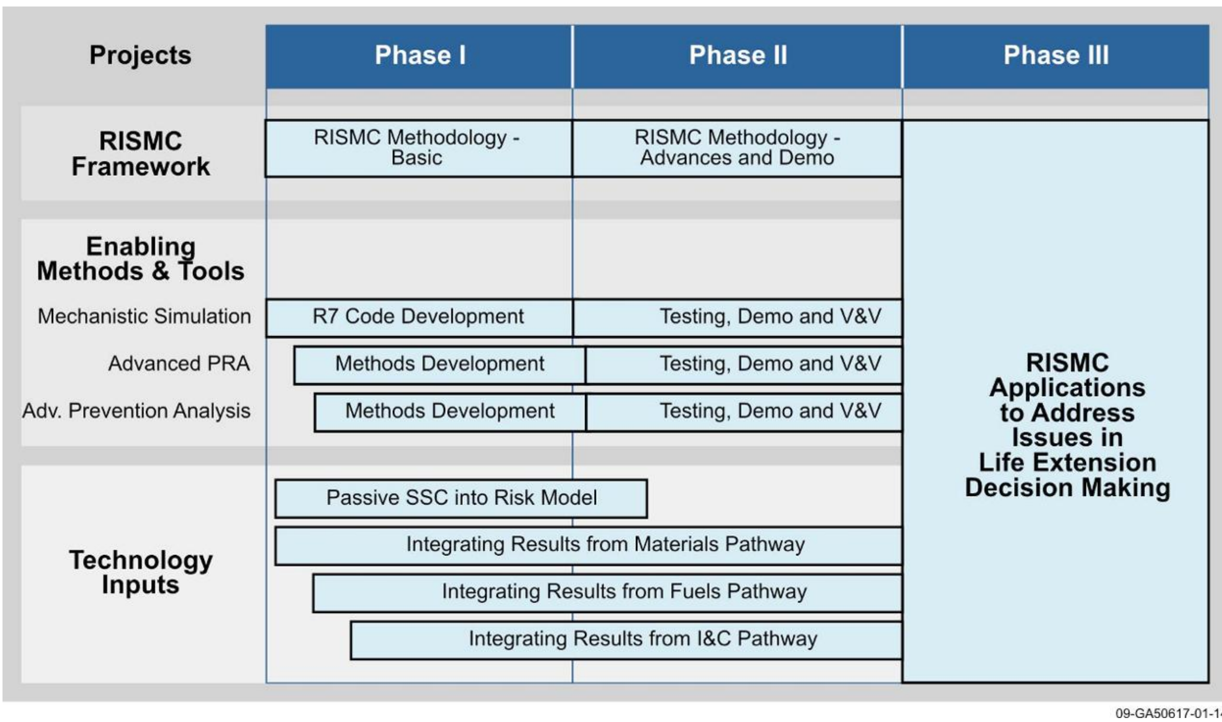

Figure 3-15. RISMC pathway implementation schedule.

3.5 Economics and Efficiency Improvement

3.5.1 Background and Introduction

Improving the economics and efficiency of current LWRs while maintaining excellent safety performance is one of the primary objectives of the LWRS R&D Program. Power uprates have been the most important methods that enable enhancement of the economic performance of the current operating fleet of LWRs. Cooling capability influences thermal efficiency and reliable operation. Increased reactor power and climate change concerns place more burdens on cooling requirements. Expanding the current fleet into nonelectric applications would further increase the value of LWR asset owners. This R&D pathway will focus on three activities: (1) alternative cooling technologies, (2) nonelectric applications (process heat), and (3) power uprate (more detailed information on each activity can be found in Appendix E).

3.5.1.1 *Alternative Cooling.* Water consumed by thermoelectric power plants (such as those fueled by coal, natural gas, and nuclear) continues to receive increasing scrutiny as new power plants are proposed and existing power plants encounter water shortages. Climate change may exacerbate the situation through hotter weather and disrupted precipitation patterns that promote regional droughts. Before 1970, thermoelectric power plants addressed their need for cooling with either fresh or saline water withdrawals for once-through cooling. Since that time, closed-cycle systems (evaporative cooling towers or ponds) have become the dominant choice, with certain impacts on water usage. Figure 3-16 shows the Limerick nuclear power plant in Pennsylvania, which uses mine pool water for a substantial fraction of its cooling.

Figure 3-16. Limerick nuclear power plant.

3.5.1.2 *Nonelectric Application (Process Heat).* Nuclear power plants have very high capital investment and low operating costs. Therefore, to minimize the cost of electricity, these nuclear power plants are typically operated at full power to provide base load needs. With the potential extended power uprates for these nuclear power plants in the future and the eventual construction of new nuclear power plants in the United States, some of the nuclear power plants may need to be operated at reduced power levels when electricity demand is low at off-peak times, such as during the night. Operating nuclear power plants at a reduced power level is certainly not desirable. On the other hand, only about one-fifth of the world's energy consumption is used for electricity generation. Most of the world's energy consumption is for heat and transportation. The existing LWR fleet in the United States has no experience in nonelectric applications. However, the existing LWR fleet might have considerable potential to penetrate into the heat and transportation sectors, which are currently served by fossil fuels that are characterized by price volatility, finite supply, and, more importantly, environmental concerns. There are a wide variety of purely thermal applications of a reactor's output, which may be integrated with an electrical generating plant. These nonelectric applications of nuclear energy include nuclear hydrogen production, providing heat and steam to industrial processes, seawater desalination, and district heating (see Appendix E for more detailed information about these applications). The desalination of seawater using nuclear energy has been demonstrated and nearly 200 reactor-years of operating experience have been accumulated worldwide. District heat involves the supply of heating and hot water through a distribution system, which is usually provided in a cogeneration mode in which waste heat from power production is used as the source of district heat. Several countries have district heating using heat from nuclear power plants.

3.5.1.3 Power Uprates. The nuclear industry has been using power uprate since the 1970s as a way of increasing the power output of its nuclear power plants. The primary methods of producing more power are changes in the fuel design, operational changes in reactor thermal-hydraulic parameters, and upgrade of the balance of plant capacity by component replacement or modification (such as replacing a high-pressure turbine). Other changes may include replacing selected feedwater and condensate motors that are already operating at capacity, providing additional cooling for some plant systems, various electrical upgrades to accommodate the higher currents and to improve electrical stability, modifications to accommodate greater steam and condensate flow rates, and instrumentation upgrades that include replacing parts, changing set points, and modifying software. As of today, NRC has approved 127 power uprate submittals. The total extra power generated from power uprate is equivalent to building five 1,000-MWe new nuclear power plants, which significantly enhanced the asset value of the plant owners. There are three types of power uprates[f] (descriptions of the power uprates are provided in Appendix E): (1) measurement uncertainty recapture power uprates are less than 2% and are achieved by implementing enhanced techniques for calculating reactor power; (2) stretch power uprates are typically up to 7% and are within the design capacity of the plant; and (3) extended power uprates are greater than stretch power uprates and have been approved for increases as high as 20%.

3.5.2 Vision and Goals

The commercial nuclear power industry will undertake more extended power uprate and ultra power uprate activities, have alternative cooling technology options ready to maximize water usage and accommodate uprated power output, and expand to nonelectric applications within the framework of plant life extension to minimize the cost of production and maximize return on investment.

The programmatic goals for this R&D pathway are captured in the following statements:

1. Power Uprates: Provide scientific and engineering solutions to facilitate extended power uprates and ultra high power uprates for all operating LWRs in a cost-effective manner. Specific goals are to enable boiling water reactors to achieve above 20% extended power uprate and pressurized water reactors to achieve up to 20% power uprate by the year 2030.

2. Alternative Cooling Technology: Conceive, develop, and establish deployable technologies for optimizing use in the nuclear energy thermocycle while minimizing reliance on water resources at the same time.

3. Nonelectric Application (Process Heat): Penetrate the applications of existing LWRs to low temperature process heat and hydrogen production market.

3.5.3 Highlights of Research and Development

3.5.3.1 Alternative Cooling. Alternatives to closed-cycle cooling (wet cooling tower) are generally dry cooling (waste heat rejected to the atmosphere) or hybrid cooling (using aspects of both wet and dry cooling), as well as replacing freshwater supplies with degraded water sources. Degraded water is polluted water that does not meet water-quality standards for various uses such as drinking, fishing, or recreation. Existing operating LWRs in the United States use either once-through cooling or wet cooling tower.

It is essential to provide adequate and timely cooling for safe and economic operation of nuclear power plants. With more stringent regulation on the temperature of the discharged cooling water from a nuclear power plant, the availability of clean cooling water, increased cooling load with the power uprates, and potential warmer weather in the summer season due to global climate change, alternative and potentially advanced cooling technology has to be developed in order to ensure the reactors can be safely and economically operated without being forced to shut down or reduce the power output due to cooling water issues. R&D activities will focus on: (1) technology development such as advanced condenser design, reducing water losses in the wet cooling tower system, improving dry cooling and hybrid cooling technology, and ice thermal storage system; (2) evaluating applicability of alternative water-conserving cooling technologies (such as dry cooling, hybrid cooling, and ice thermal storage system) to improve LWR plant efficiency and relieve the cooling water requirement, as well as expand use of alternative

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f. http://www.nrc.gov/reactors/operating/licensing/power-uprates/type-power.html.

sources of water; and (3) improving analysis methodology and performing actual analysis to identify optimal designs and developing water resource assessment and management decision support tools (more detailed information on these technologies is found in Appendix E).

3.5.3.2 Nonelectric Application (Process Heat). Nuclear power plants produce 1,500 to 4,500 MW of steam. Very few markets exist for such large quantities of steam. Usually, it is not economical to modify a nuclear power plant to produce a few megawatts of heat to meet a local industry or district-heating need; therefore, district heating will not be considered. Under current circumstances, seawater desalination using existing LWRs also is a very remote possibility. However, biomass-to-fuel-ethanol plants require very large quantities of low-temperature steam. Using nuclear energy for transportation indirectly through transportation fuel ethanol production has the potential to open new markets for existing LWRs. For example, low-temperature steam from nuclear power plants can be extracted to help produce ethanol from starch.

Steam from nuclear power plants also can be used to provide process heat to a Fischer-Tropsch chemical process (or similar processes) to produce synthetic fuel. Coal gasification has the advantage of the reduction of air emissions from coal combustion, an increased thermal efficiency of combustion, and use of a large resource base. If coal gasification becomes widespread, economic and environmentally benign technologies for the supply of gasification energy will be required. Nuclear energy, being an industrially proven and nonpolluting technology, is a valid candidate for this purpose.

Using nuclear energy to produce hydrogen is likely to facilitate another application of nuclear energy. The share of nuclear energy in a hydrogen-based system will depend on its competitiveness with other energy options such as natural gas. Successful demonstration projects (such as use of surplus nuclear capacity for hydrogen production using cheap off-peak electricity) would help promote the nuclear-hydrogen link.

The technical and economic viability of different applications will be studied. One key issue to be addressed is interface design and plant modifications. Appendix E provides further details on low-temperature distillation, nuclear hydrogen production, and heat source for synthetic fuel production.

3.5.3.3 Power Uprates. R&D activities will be focused on enabling safe and cost-effective plant modifications and modernizations required to gain margins by enhancing the plant power limiting equipment capability. Consistent with the main themes currently identified in this R&D pathway, activities are planned in the following main areas to significantly uprate the current LWR power levels (details on each of these activities can be found in Appendix E):

1. Collaboration with Nuclear Materials Aging and Degradation R&D Pathway

2. Fuel performance and loading management

3. Reactor thermal hydraulics

4. Safety assessment under high power

5. Balance of plant, including steam generators for pressurized water reactors

6. Operation with higher core outlet temperature

7. Instrumentation and control systems and software reliability

3.5.4 Products and Implementation Plan

The main products of this pathway are as follows:

- Advanced cooling technologies that would reduce cooling water requirements and improve the plant's thermal efficiency

- Tools, methods, and technologies (collaborating with the other four pathways) to enable more extended power uprates or even ultra high power uprates

- Feasibility studies of the technical and economic viability of expanding the existing fleet into nonelectric applications.

The implementation schedule (Figure 3-17) is structured to support the following high-level milestones:

- 2015: Preserve the once-through cooling technologies (advanced water conservation technologies for wet cooling tower).

- 2015: Complete feasibility studies for nuclear hydrogen production and low temperature distillation applications.

- 2020: Ensure significant cost reduction of dry cooling technology and thermal efficiency improvement in the hot summer timeframe.

- 2020: Ensure next generation safety analysis tools available to support extended power uprates and ultra power uprates.

- 2025: Apply advanced cooling technologies.

- 2030: Enable 10-GWe extra capacity additions through more extended power uprates or even ultra high power uprates.

	Phase I	Phase II	Phase III
Alternative Cooling Technology	Preserve once-through technology Development of water conservation technology for wet cooling tower	Cost reduction and efficiency improvement for dry and hybrid cooling technology	Application of advanced cooling technologies
Non-electirc Applications	Technology and economics viability	Interface design	Applications
Power Uprate	Collaborate with other pathways to enable 10 GWe extra capacity addition through power uprates, with a stretch goal of 20 GWe		

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Figure 3-17. Economics and Efficiency Improvement pathway implementation schedule.

3.6 Pathway Crosscutting and Integration

The overall focus of the R&D activities will be on practically advancing the ability of the owner of nuclear assets to manage the effects of the aging of passive components and increase the efficiency and economics of operations. Transformational activities initially should be developed as limited-scope pilots that provide obvious, value-driven return for the asset owner. In selecting projects, it is vital that all consideration be given to how each of the pathways can support achievement of safety and economic sustainability for existing LWRs by ensuring that each pathway is appropriately coordinated with the desired outcomes of the other pathways. Technical integration is an important and significant part of the LWRS R&D Program. R&D within the program is integrated across scientific and technical disciplines in the five R&D pathways. The LWRS R&D Program is integrated with outside sources of information and parallel R&D programs in industry, universities, and other laboratories, both domestic and international. Different methods of integration are used depending on the situation and goals.

3.6.1 Technical Integration

Interfaces between R&D pathways and the required integration across them are naturally defined by common objectives for materials and fuel performance and the system monitoring of their performance. Similarly, interface and integration of the pathways with the RISMC R&D pathway is defined by data and models, which affect performance, monitoring, and control (Figure 3-18).

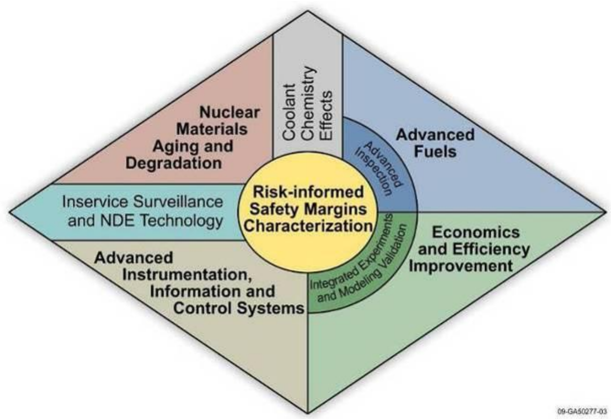

Figure 3-18. Integration of five research and development pathways.

Data and information from the Nuclear Materials Aging and Degradation, Advanced LWR Nuclear Fuel, and Economics and Efficiency Improvement R&D pathways will be fed into the RISMC models. Results of the RISMC analysis will guide development of advanced fuels; materials aging and degradation mitigation; advanced II&C systems; and economics and efficiency improvement. Table 3-1 includes examples of some crosscutting areas in the LWRS R&D Program.

3.6.2 Enhanced Modeling as a Crosscutting Activity

The most common theme from all five R&D pathways is use of computer modeling of physical processes or development of a larger system computer model. Extensive use of computer modeling by all five R&D pathways is intended to distill the derived information so that it can be used for further research in other pathways and as the basis for decision making.

Computer modeling occurs in three forms with many overlapping aspects within the LWRS R&D Program. Modeling a physical behavior (such as crack initiation in steel) is an example of direct computer modeling. The resulting model is used to store information for use in other pathways and to use in its own right for further research.

A second computer modeling activity is development of more detailed computer modeling tools capable of encoding more complex behaviors. One of the intended outcomes from Advanced LWR Nuclear Fuels Development research are new modeling tools that can describe behavior of such complexity that current computer models are incapable of producing adequate results for the LWRS R&D Program. The increased accuracy will allow improved results to be incorporated into other pathways.

Table 3-1. Program crosscutting areas.

Crosscutting Area	Materials Aging and Degradation	Advanced Fuels	Advanced II&C	RISMC	Economics and Efficiency Improvement
Coolant chemistry effects	X	X	X	X	X
Crack growth mitigation effects	X	X		X	X
Irradiation testing	X	X			
Irradiation source term changes		X		X	
Improved online monitoring of reactor chemistry	X	X	X	X	X
Advanced instrumentation for the study of system degradation	X		X	X	X
Fuel failure mechanisms		X		X	X
Creation of SSC aging database	X		X	X	X
Advanced measurement techniques	X	X	X	X	X
Field testing and data collection/capture	X	X	X	X	X
Nondestructive evaluation/assay tools	X	X	X	X	X
Advanced inspection techniques	X	X	X	X	X

The final computer modeling improvement is creation of larger integrated databases that roll up results and allow decision-making. The large system-wide, integrated models allow complex behavior to be understood in new ways and new conclusions to be drawn. These integrated databases can be used to further guide physical and modeling research, improving the entire program.

Because of their overlapping nature and personal interfaces, these modeling activities tend to be natural crosscutting activities between R&D pathways. Computer modeling will remain an integrating and crosscutting element of the LWRS R&D Program.

3.6.3 Coordination with other Research Efforts

In order to encourage communication and coordination with outside experts and parallel programs, the LWRS R&D Program will be aware of issues and changes of technical needs that affect long-term, safe, and economical operation of existing operating LWRs, and share information and resources with other professionals and programs that can assist the LWRS R&D Program to provide timelier, less expensive, and better solutions to the needs and issues.

Primarily, coordination will be with the EPRI Long-Term Operation Program. At the program level, formal interface documents will be used to coordinate planning and management of the work. This will provide a ready source of information from EPRI’s Nuclear Power Council and through their contact with utilities. At the R&D project level, both programs encourage frequent communication and collaboration.

Consistent with the vision of the LWRS R&D Program, working relationships have been established with international organizations in FY 2009 and will continue in FY 2010 and beyond. The goal is to facilitate communication and cooperative R&D with international R&D organizations.

3.6.4 Performance of Technical Integration and Coordination

The LWRS R&D Program will lead and encourage technical integration and coordination of issues affecting the LWR long-term operation program using methods that best match the issue. For known gaps in data, understanding, or technology, the LWRS R&D Program will plan and manage integrated R&D projects through the LWRS R&D Program Technical Integration Office (TIO) and its multiple interfaces.

To accommodate currently unknown issues or gaps in technology that may arise as result of ongoing R&D or nuclear power plant operations, a broader approach is necessary. This approach should include active internal and external communication with professional organizations, industry groups, and interdisciplinary teams for project and program reviews. The Steering Committee is an essential part of this process. The LWRS R&D Program encourages participation in professional technical societies and national standards committees.

4. PROGRAM MANAGEMENT

4.1 Organization Structure

The entire LWRS R&D Program falls within the DOE Office of Nuclear Energy. Program management and oversight, including programmatic direction, project execution controls, budgetary controls, and TIO performance oversight is provided by the DOE Office of LWR Technologies in conjunction with the DOE Idaho Operations Office (DOE-ID) (Figure 4-1).

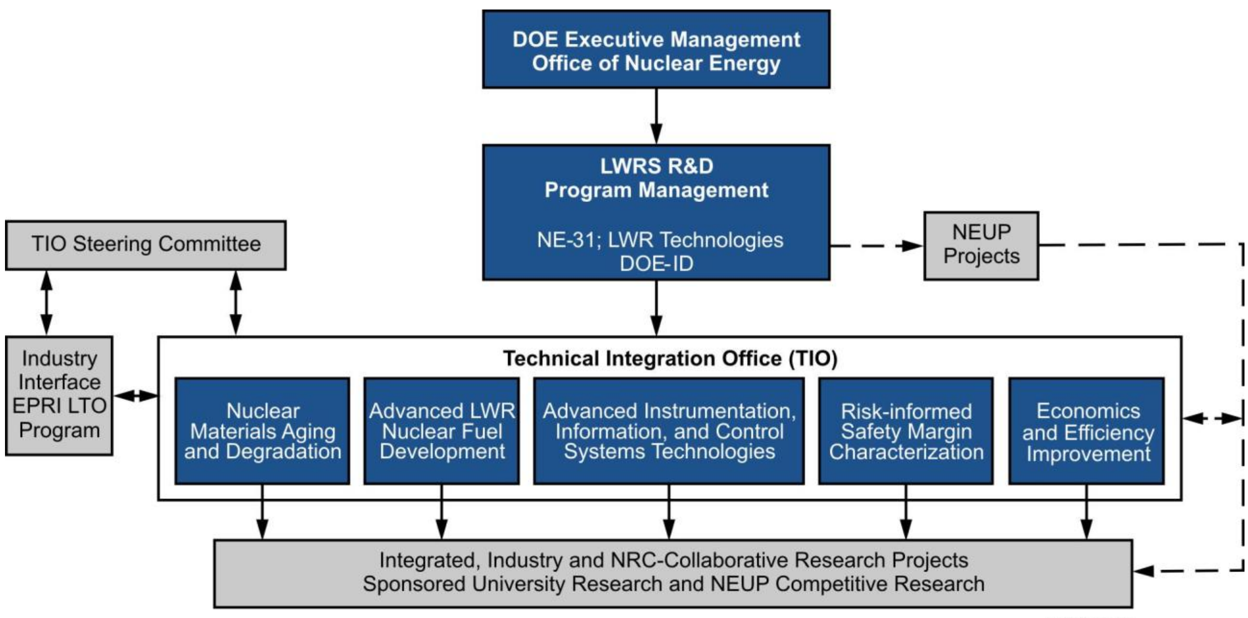

Figure 4-1. Program organization.

DOE-ID will provide technical and administrative support to the LWRS R&D Program. This support includes activities such as assisting in development of administrative requirements in support of contracting actions, conducting merit reviews and evaluations of applications received in response to program solicitations, performing all contracting administration functions, and providing technical project management and monitoring of assigned projects.

The TIO basic organizational structure is used to accommodate the crosscutting nature of the proposed research pathways. This organization is responsible for developing and implementing integrated research projects consistent within the LWRS R&D Program vision and objectives. Additionally, the TIO is responsible for developing suitable industry and international collaborations appropriate to individual research projects and acknowledging industry stakeholder inputs to the program.

Within the TIO structure is the TIO Director, each of the five R&D pathway leads, and an external Steering Committee. Nuclear industry interfaces and stakeholders' contributions are accommodated in program development and project implementation actions through the TIO management structure. Recognition of continuing industry collaborations reflecting issues and concerns necessary to extend plant licenses are incorporated through the same program development and implementation actions.

The functional organization, reporting relationships, and roles and responsibilities for the TIO are explained in the following sections and are shown in Figure 4-2.

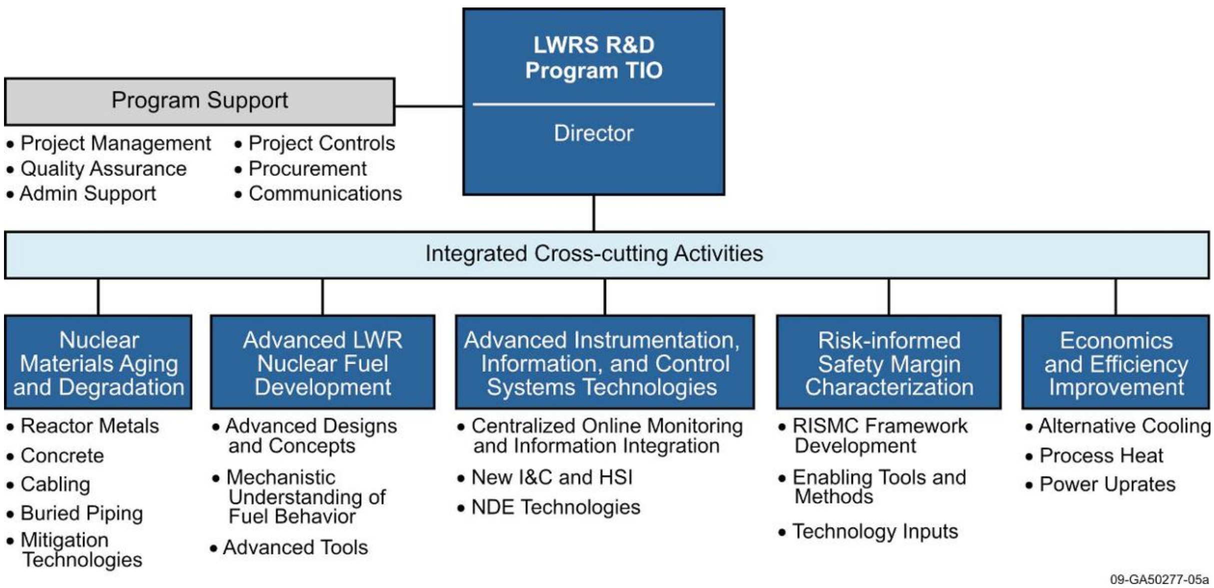

Figure 4-2. Technical Integration Office organization.

4.2 Roles, Responsibilities, Accountabilities, and Authorities

4.2.1 Department of Energy Program Office of Nuclear Energy

DOE is responsible for the Federal government's investments in nuclear power research, development, demonstration, and incentive programs, which all further the nation's supply of clean, dependable nuclear-generated electricity. The LWRS R&D Program conducts research that enables licensing and continued reliable, safe, long-term operation of current nuclear power plants beyond their initial license renewal period. The DOE Office of LWR Deployment directs the program, establishes policy, and approves scope, budget, and schedule for the program through the LWRS R&D Program Manager. The DOE LWRS R&D Program Manager is assisted with program management and oversight by DOE-ID.

The essential programmatic DOE functions include, but are not limited to, the following:

- Establish program policy and issue program guidance

- Establish requirements, standards, and procedures
- In cooperation with the TIO, establish requirements and develop strategic and project plans
- Establish performance measures and evaluate progress
- Represent the DOE program to other government agencies.

4.2.2 Technical Integration Office

TIO supports the DOE Program Manager. The program is a cost-shared, collaborative program aimed to meet the needs of a diverse set of stakeholders. In addition to supporting national policy (energy and environmental security needs), the program supports agreed upon technical needs of NRC in assessing safety and relicensing requests for nuclear power plant extended life operation. It also supports industry needs for data and planning tools for long-term safe economical operation of their nuclear power plants. TIO is staffed with a director, R&D pathway leads, and program management staff. The director and leads are all well-known technical and management experts from DOE laboratories. The TIO is structured and staffed to provide the program director with strong interfaces and communications with stakeholders, R&D plans based on stakeholder needs, proposals for R&D-specific projects and budgets, management of the projects, including funding, and communication of the results.

The LWRS R&D Program TIO is a national organization and is expected to have international participants as the LWRS R&D Program evolves. The intent of the organization is to staff the program with the right people to accomplish the work, regardless of location or affiliation. As appropriate, the technology integration and execution activities will use facilities and staff from multiple national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries.

TIO functions include the following:

- Maintaining the long-range technical strategy plan for the LWRS R&D Program
- Maintaining the LWRS R&D Program Plan
- Developing annual project scope statements
- Developing and implementing the project execution plan
- Monitoring authorized project work
- Coordinating weekly/monthly status meetings
- Coordinating periodic technical review meetings
- Providing formal status reporting
- Maintaining baseline change control
- Performing project closeout planning and completion.

4.2.2.1 Technical Integration Office Director. The TIO director provides general program management for the LWRS R&D Program. This position leads the planning, performance, and communication of results from the R&D pathways. The TIO director works with the program support team and R&D pathway leads to integrate and ensure all requirements are well defined, understood, and documented through long-range planning. The TIO director works with the project support staff to ensure proper annual financial planning, scoping, oversight, and scheduling of the project work. The TIO director and the Steering Committee oversee assignment of appropriate resources and evaluate and resolve R&D needs of the LWRS R&D Program. The TIO director reports to DOE Program Manager.

4.2.2.2 R&D Pathway Leads. The TIO currently includes five R&D pathway leads for the major R&D areas currently developed. The leads are the technical managers for their pathways and are responsible for ensuring that technical planning, project management, and leadership is provided for each pathway. R&D pathway leads are the primary interface between technically diverse organizations that form the structure of the LWRS R&D Program. They are responsible for integration and translation of project requirements into an overall program plan tailored to accomplish their assigned R&D mission. They are responsible for establishing scope, cost, and schedule of the R&D activities. They interface with other R&D pathway leads to ensure effectiveness of crosscutting activities.

4.2.2.3 Program Support Team. The program support staff is responsible for contractual operations of TIO and assists other parts of TIO to execute work. The team provides personnel with expertise in project management, quality assurance, procurement, project controls, and communications. They provide tools, structure, oversight, and rigor to maintain R&D schedules and interfaces to the LWRS R&D Program; provide financial information to management (through the TIO director's office); monitor technical progress and earned value; and track milestones***.***

4.2.3 Project Monitoring and Evaluation

DOE and TIO use a variety of methods to provide oversight of their projects, including semiannual project reviews, periodic progress reports, and scheduled evaluations, invoice reviews, and participation in periodic project meetings and conference calls.

4.2.3.1 ***Project Reviews***. DOE and TIO conduct semiannual and annual project progress review meetings with the project participants, including all research pathway leaders. During these project review meetings, project activities, schedule progress, and cost are discussed in detail. Status of deliverables, funding, or schedule concerns and potential changes in scope are discussed. Performance expectations for the remainder of the budget period and project are reviewed. On an annual basis, DOE staff reviews the work scope, budget requirements, schedule, deliverables, and milestones for the subsequent budget periods as part of the approval of project continuation requests. Review of these continuation requests often requires face-to-face meetings with project participants to fully understand the future planned work.

4.2.3.2 ***Periodic Project Status Meetings and Conference Calls***. DOE, TIO, and pathway leaders participate in periodic project status meetings and conference calls. Typically, project conference calls are the method of choice because of the number and location of participants; they are held at least twice a month. In addition, DOE staff participates in TIO conference calls on specific tasks.

4.2.3.3 ***Monthly Progress and Earned Value Reporting.*** DOE personnel review and evaluate project monthly progress reports for the project task and activity progress, accomplishment of deliverables, and budget and cost status. Because of the size, cost, and complexity of integrated LWRS projects and collaborative projects, earned value will be reported on a monthly basis. This earned value reporting provides project participants and DOE staff with a monthly snapshot of overall project cost and schedule performance against the project baseline.

4.3 INTERFACES

The LWRS R&D Program TIO is intended as a national organization and is expected to have multiple national laboratory, governmental, industrial, international, and university partnerships. As appropriate, the LWRS R&D Program technology development and execution activities will use facilities and staff from national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries.

TIO is responsible for ensuring the necessary memorandum purchase orders, interagency work orders, or contracts are in place to document work requirements, concurrence with work schedules and deliverables, and transfer funds to the performing organizations for R&D activities.

4.3.1 Steering Committee

A standing TIO Steering Committee advises TIO on the content, priorities, and conduct of the program. The committee is comprised of technical experts selected and agreed upon by the TIO director and the DOE Program Manager. The committee, as a group, is knowledgeable of the various R&D needs of DOE, industry, and NRC; ongoing and planned research as related to nuclear power technology; and policies and practices in public and private sectors that are important for the collaborative R&D program. The TIO director, in consultation with the Steering Committee, may form ad hoc subcommittees to review specific technical issues.

4.3.2 Industry Partners

Planning, execution, and implementation of the LWRS R&D Program are done in coordination with U.S. industry and NRC to assure relevance and good management of the work. The LWRS R&D Program addresses some of the most pressing R&D needs identified in the Strategic Plan, including R&D needed by currently operating LWRs to extend their safe economical lifetime to significantly contribute to the long-term energy security and environmental goals of the United States. EPRI has established the Long-Term Operations Program to run in parallel with the DOE LWRS R&D Program. The Long-Term Operations Program is based on the LWR R&D Strategic Plan and focuses on the long-term operations of the current fleet. EPRI and industry’s interests are applications of the scientific understanding and the tools to achieve safe, economical, long-term operation. Therefore, the government and private sectors’ interests are similar and interdependent, leading to strong mutual support for technical collaboration and cost sharing. Formal interface agreements between EPRI and the TIO will be used to coordinate collaborations. Contracts with EPRI or other businesses may be used as appropriate for some work.

4.3.3 International Partners

TIO has made contact with several international organizations with interests and programs in long-term operation of LWR technology and the R&D to support those interests and programs. We expect to continue to develop these contacts to provide timely awareness of emerging issues and their scientific solutions. A close working relationship with the Organization for Economic Cooperation and Development’s Halden Project and with Electricite de France’s Materials Aging Institute are particularly important to the LWRS R&D Program. As funding is available, the LWRS R&D Program intends to initiate formal R&D agreements with both institutions.

4.3.4 University Partners

Universities will participate in the program in at least two ways: (1) through the Nuclear Energy University Program and (2) with direct contracts. In addition to contributing funds to the Nuclear Energy University Program, the LWRS R&D Program will provide to the Nuclear Energy University Program descriptions of research from universities that would be helpful to LWRS R&D Program. In some cases, R&D contracts will be let to key university researchers.

4.3.5 NRC Partnership

DOE's mission to develop the scientific basis to support both planned lifetime extension up to 60 years and lifetime extension beyond 60 years and to facilitate high-performance economic operations over the extended operating period for the existing LWR operating fleet in the United States is the central focus of the LWRS R&D Program. Therefore, more and better coordination with industry and NRC is needed to ensure that there is a single national strategic plan, shared objectives, and efficient integration of collaborative work for LWRS. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that is executed among these groups. NRC has a memorandum of understanding[g] in place with DOE, which specifically allows for collaboration on research in these areas. Although the goals of NRC and DOE research programs differ in many aspects, fundamental data and technical information obtained through joint research activities is recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and to avoid needless duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost sharing may be done in a mutually beneficial fashion.

[g] "Memorandum of Understanding Between U.S. Nuclear Regulatory Commission and U.S. Department of Energy on Cooperative Nuclear Safety Research," dated April 22, 2009, and signed by Brian W. Sheron, Director, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission and Rebecca Smith-Kevern, Acting Deputy Assistant Secretary for Nuclear Power Deployment, Office of Nuclear Energy, U.S. Department of Energy.

5. BUDGET SUMMARY

Table 5-1. Five-year program budget profile by work breakdown structure ($K).

			FY-09	FY-10	FY-11	FY-12	FY-13	>FY-13[1]
1.0	Light Water Reactor Sustainability Program							
1.1	Management		481	3,100	8,600	14,500	22,000	28,000
	1.1.1	Technical Integration Office (TIO)						
	1.1.2	DOE Headquarters Program Management[2]						
	1.1.3	Program Controls						
1.2	Materials		602	2,000	6,000	10,000	15,000	20,000
	1.2.1	Project Management at Oak Ridge National Laboraroty						
	1.2.2	Reactor Metals						
	1.2.3	Concrete						
	1.2.4	Cabling						
	1.2.5	Buried Piping						
	1.2.6	Mitigation Technologies						
	1.2.7	Integrated Research Activities						
1.3	Fuels		480	1,900	5,000	9,000	15,000	18,000
	1.3.1	Project Management at INL						
	1.3.2	Advanced Designs and Concepts						
	1.3.3	Mechanistic Understanding of Fuel Behavior						
	1.3.4	Advanced Tools						
1.4	Instrumentation Information Systems Technologies		208	900	4,000	6,000	7,000	9,000
	1.4.1	Project Management at INL						
	1.4.2	Centralized Online Monitoring and Information Integration						
	1.4.3	New Instrumentation and Control and Human System Interfaces and Capabilities						
	1.4.4	Nondestructive Examination Technologies						
1.5	Risk-Informed Safety Margin Characterization		229	2,100	5,400	8,000	11,000	15,000
	1.5.1	Project Management at INL						
	1.5.2	RISMC Framework						
	1.5.3	Technology Integration						
	1.5.4	Enabling Methods and Tools						
	1.5.5	Technology Inputs						
1.6	Economics and Efficiency Improvements				1,000	2,500	5,000	10,000
	1.6.1	Project Management at INL						
	1.6.2	Alternative Cooling						
	1.6.3	Process Heat						
	1.6.4	Power Uprates						
Grand	Totals		2,000	10,000	30,000	50,000	75,000	100,000

1. Steady-state, long-term funding levels.
2. Includes Nuclear Energy University Program (20% of total budget) and SBIR/STTR (2.8% of total budget) after FY 2009. For FY 2009, a Nuclear Energy University Program project was funded under the Gen-IV Program and is not included here.

6. APPENDIXES

Appendix A, Nuclear Materials Aging and Degradation

Appendix B, Advanced Light Water Reactor Nuclear Fuel Development

Appendix C, Advanced Instrumentation, Information, and Control Systems Technologies

Appendix D, Risk-Informed Safety Margin Characterization

Appendix E, Economics and Efficiency Improvement